Carbon and Energy in Ecosystems Diagnostic Question Clusters
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Introduction

Understanding ecological processes requires an understanding of smaller scale processes such as those at the molecular, cellular and organismal scales. The diagnostic question clusters (DQC's) created for this project are designed to help professors unpack their students understanding of ecological processes, identifying smaller scale problems that limit large scale understanding.

The created DQC's include a multiple process "umbrella" question followed by several single process questions that help to gauge student understanding of smaller scale processes that limit their ability to understand the "umbrella" question. Based on preliminary analysis of student responses, we've identified 10 DQC's to include in this project. All 10 of the chosen DQC's are organized around topics commonly found in introductory ecology classes, and less so in introductory biology classes.

DQC's are organized into five main topics, with two DQC's in each topic. The organization is shown in the table below. Most of the DQC's will be improved based on previous student responses, but the primary structure will remain the same.

	DQC Topics				
	Carbon Cycling	**Trophic Levels**	**Energy Flow in Ecosystems**	**Understanding Climate Change**	**Carbon Dynamics in Energy Production**
DQC 1	Forest Carbon	Carbon in Nature	Energy Pyramid	Carbon Balance	Biofuels
DQC 2	Grandma Johnson	Trophic Transfer	Rainforest	Keeling Curve	Gasoline

Carbon Cycling DQC's

Conservation of matter is a principle that must be applied to understand concepts in ecosystem ecology. **Forest Carbon** and **Grandma Johnson** are two parallel diagnostic question clusters (DQC's) designed to diagnose student ability to trace carbon through ecosystems. Each DQC begins with an ecosystem scale question about ecosystem carbon cycling that requires students to apply multiple carbon transformation processes in order to provide a correct answer. Within each DQC, subsequent questions ask students to display knowledge of individual processes that are occurring in the initial multiple process question. This design will allow you, the instructor, to identify what processes students don't understand, which are preventing their understanding of ecosystem carbon cycling. The names of individual questions categorized by process are shown in the table below.

Processes	**Forest Carbon**	**Grandma Johnson**
Multiple Process	CARBPOOL (1)	GRANJOHN (1)
Transformation – Plant to Plant	CARBPATHSB (5b)	CARBPATHSB (4b)
Transformation – Plant to Soil	CARBPATHSD (5d)	CARBPATHSD (4d)
Transformation – Plant to Animal	CARBPATHSC (5c)	CARBPATHSC (4c)
Transformation – Animal to Animal		COYOTE (5)
Photosynthesis	PLANTRESP2 (2), PLANTRESP1 (3), MASSCHANGE (6a)	MAPLEMASS (3)
Respiration – Decomposition	SOILRESP (4), MASSCHANGEC (6c)	BREADMOLD (2), POTATOMASS (6)
Respiration – Plants	CARBPATHSA (5a), PLANTRESP2 (2), PLANTRESP1 (3)	CARBPATHSA (4a)
Respiration – Animals	PLANTRESP1 (3), MASSCHANGEB (6b)	

Forest Carbon Balance Diagnostic Question Cluster

Carbon transformations are occurring everywhere in a forest. Plants are photosynthesizing, generating organic carbon from carbon dioxide. Organic carbon is being transformed into other organic sources within plants, and between organisms through processes such as biosynthesis and digestion. All organisms are involved in respiration, converting organic carbon sources into inorganic forms. Students must consider all of these carbon transformation processes to provide a proper rationale for their answer to question one about the balance of carbon in a forest (the multiple process question). Even though question one is asking about a process at the ecosystem scale, knowledge of carbon cycling processes at the molecular and organismal scales are necessary for proper understanding of the ecosystem based question. The individual carbon cycling processes involved are posed to students in questions 2-6, enabling teachers to correctly diagnose carbon cycle misunderstandings that limit correct explanations to question one of this DQC.

Forest Carbon Balance Diagnostic Question Cluster

Please answer the questions below as carefully and completely as you can.

1. In an old growth forest, which of these statements would you expect to be true?
   A) An old growth forest absorbs more carbon dioxide than it releases
   B) An old growth forest releases more carbon dioxide than it absorbs
   C) An old growth forest absorbs and releases about the same amount of carbon dioxide

Please explain your answer.

A forest absorbs carbon dioxide through photosynthesis, and releases carbon dioxide during respiration by plants, animals and decomposers. As a forest matures and gets older, plants do not grow as fast, and the rate at which carbon is being absorbed is reduced, becoming close to the rate at which carbon dioxide is released through respiration.

Processes = Multiple Processes, **Principles** = Tracing Matter, **Scale** = Ecosystem

Interpreting Student Responses: Students must understand that trees both photosynthesize and respire, that net carbon dioxide exchange between the forest and atmosphere is the summation of the photosynthesis and respiration occurring in all individual organisms, and that old growth forests are not experiencing a net gain of carbon because the trees aren't growing.
The most sophisticated answers will involve model based explanations describing the balance among photosynthesis, carbon allocation, and respiration. *"Because an old growth forest absorbs less CO_2 due to a slower growth rate and then less need for sunlight, compared to the decomposition and respiration rate/CO_2 output it would have."* Some students may think that plants photosynthesize/take in CO_2, but do not respire/release CO_2 suggesting that they do not understand the role of respiration. Some students think older trees photosynthesize more and respire less than younger trees, suggesting that they may not understand carbon allocation within plant.

2. In plants, …
   A) photosynthesis occurs but there is no respiration.
   B) photosynthesis occurs in the light and respiration occurs in the dark.
   C) respiration occurs 24 hours a day and photosynthesis occurs in the light.
   D) photosynthesis and respiration occur but not at the same time.
   E) Responses B. and C. are correct.

Processes = Photosynthesis, Respiration, **Principles** = Tracing Matter, **Scale** = Organismal

Interpreting Student Responses: This question assesses whether students understand that plants both photosynthesize and respire, and whether they understand when these processes occur within the organism. Students who answer A and D are not tracing matter (carbon) once it is in the plant. They likely do not understand the role of respiration

3. Considering the cellular processes of photosynthesis and respiration, which statements are true? Circle True (T) or False (F) for each response.
   T **F** Photosynthesis is the process by which plants respire.
   T F Both animals and plants respire and release CO_2.
   T **F** During respiration, animals release CO_2 and plants release O_2.

T **F** During respiration, animals release O_2 and plants release CO_2.

Processes = Photosynthesis, Respiration, **Principles** = Tracing Matter, **Scale** = Organismal

Interpreting Student Responses: This question assesses whether students understand the reactants and products of photosynthesis and respiration, and whether they understand that plants photosynthesize and respire, but animals only respire.

Students who answer True to choice A do not know the purpose of photosynthesis and/or are not familiar with the term respire. Students who answer False to choice B may think that plants do not respire. Students who answer True to choice C may think that respiration means gas exchange (organismal level) and that plants only release O_2 (plants only photosynthesize) and animals release CO_2. Students who answer True to choice D may be unfamiliar with term respiration and/or they do not know the correct chemical products of respiration.

4. Circle all correct answers. In most terrestrial ecosystems, soil respiration ...

A) happens when rocks break down.
B) is not linked to decomposition rates.
C) typically decreases as soil moisture increases
D) refers to respiration by organisms living in the soil.
E) typically decreases as temperatures increases
F) Includes gases from plant roots

Processes = Respiration, **Principles** = Tracing Matter, **Scale** = Organismal

Interpreting Student Responses:
Rationale: This question assesses whether students understand that soil organisms undergo respiration as part of the decomposition process and that cells within plant roots respire. The question also requires students to understand that both temperature and moisture affect the activity level of decomposers.

Students who answer A may think that rocks contain gases that are released when rocks weather/break down.
Students who answer B do not understand that decomposition is the oxidative process by which organic carbon is converted to inorganic CO2.
Students who answer C do not understand that soil water affects the activity of the soil organisms that carry out respiration. Lower activity results in lower respiration.
Students who answer E do not understand that temperature affects the activity of the soil organisms that carry out respiration. Lower activity results in lower respiration.

5. Once carbon enters a plant, it can …

A) exit the plant as CO_2. Circle **True** or False
Explain

Cellular respiration occurs in plants, which would result in the loss of carbon dioxide to the atmosphere.

B) become part of the plant cell walls, protein, fat, and DNA. Circle **True** or False
Explain

Glucose is utilized throughout the plant to synthesize various organic molecules, including structural, functional and genetic molecules.

C) be consumed by an insect feeding on the plant and become part of the insect's body. Circle **True** or False
Explain

All parts of a plant contain carbon. An insect obtains its carbon from eating organisms in lower trophic levels, including plants. The carbon molecules that an insect consumes are digested, transported through the body and incorporated into various molecules within the insect.

D) be converted to energy for plant growth. Circle True or **False**
Explain

Matter and energy are coupled, but not interchangeable. The bonds between carbon atoms in a plant contain chemical energy, but carbon atoms cannot be converted to energy.

E) become part of soil organic matter when parts of the plants die and fall off the plant. Circle **True** or False
Explain

Plant parts that enter the soil are generally decomposed by soil organisms. Some of the carbon that was part of the plant enters the atmosphere as carbon dioxide during decomposition, but some of the carbon atoms remain in organic molecules in the soil, which are not decomposed immediately.

Processes = Photosynthesis, Transformation, Respiration, **Principles** = Tracing Matter, **Scale** = Organismal

Interpreting Student Responses: This question assesses whether students see multiple fates of carbon within a plant and whether they can accurately trace the path of carbon. Sophisticated answers will include process-based explanations. Choices A, B, and C require an atomic-molecular understanding of carbon transformation (e.g. – molecules are made of atoms, one atom cannot become another, many types of molecules can contain carbon). Choice D might uncover the misconception that matter can be converted to energy. To reason about choice E, students must know what soil organic matter is and the role of decomposition in the carbon cycle.

How do each of the processes below affect the mass of the systems where they are occurring?

6a. When a plant absorbs CO_2 and releases O_2 during photosynthesis:

A) The process increases the mass of the plant
B) The process decreases the mass of the plant
C) The process does not affect the mass of the plant.

Please explain your answer.

Plants take in carbon dioxide during photosynthesis and release oxygen gas. The carbon molecules are converted from carbon dioxide to organic forms, and many are incorporated into plant tissues, thus increasing the mass of the plant.

6b. When an animal breathes in O_2 and breathes out CO_2:

A) The process increases the mass of the animal

B) The process decreases the mass of the animal

C) The process does not affect the mass of the animal.

Please explain your answer.

During cellular respiration, an animal releases carbon dioxide and takes in oxygen. The carbon dioxide molecule has more mass than the oxygen molecule, and the carbon in the carbon dioxide was previously in an organic molecule within the animal.

6c. When leaves in the soil decay:

A) The process increases the mass of the soil

B) The process decreases the mass of the soil

C) The process does not affect the mass of the soil.

Please explain your answer.

Dead leaves in the soil decay, which means they are decomposed. During decomposition, soil organisms break down organic carbon molecules, using the chemical bond energy they contain, and releasing carbon dioxide to the atmosphere.

Processes = Photosynthesis, Respiration, **Principles** = Tracing Matter, **Scale** = Atomic-Molecular/Organismal

Interpreting Student Responses

This question involves tracing matter and requires that students have an understanding of the mass of atoms and molecules. Students could correctly answer 6a if they simply know that photosynthesis is the process by which plants grow/add mass and/or if they know can add the atomic weights of the molecules that enter the plant and the molecules that exit the plant during photosynthesis. Students could correctly answer 6b if they compare the atomic weight of what enters the animal (O_2) to the atomic weight of what exits the animal (CO_2). Students commonly think that gasses do not have mass. To answer 6c, students must be able to trace matter/carbon from the dead plant through decomposers and to the atmosphere. They need to know that leaves are made of carbon, that decay is the result of cellular respiration in decomposers that are eating the leaves, that cellular respiration produces CO_2, and that CO_2 diffuses from the soil to the atmosphere.

Grandma Johnson Diagnostic Question Cluster

"Grandma Johnson" (Ebert-May et al. 2003) is an excellent multiple process question for diagnosing student reasoning about various dynamics in the carbon cycle. Students must trace carbon from organic sources in Grandma Johnson, through cellular respiration by decomposers and into the atmosphere as carbon dioxide, into plants via photosynthesis and biosynthesis, to herbivores via digestion and biosynthesis that eat the plants and finally to the coyote, which consumes an herbivore. The question specifically asks about multiple organisms, making it an ecosystem level question, but knowledge of organismal and molecular scale processes is required to understand the true pathway that carbon atoms take from Grandma Johnson to the coyote. Questions 2-6 are designed to further diagnose and interpret student reasoning about specific processes in the carbon cycle, which must be properly applied to correctly answer the multiple process, Grandma Johnson question.

Ebert-May, D., J. Batzli and H. Lim (2003). "Disciplinary research strategies for assessment of learning." Bioscience **53**(12): 1221-1228.

Grandma Johnson Diagnostic Question Cluster

Please answer the questions below as carefully and completely as you can.

1. Grandma Johnson had very sentimental feelings toward Johnson Canyon, Utah, where she and her late husband had honeymooned long ago. Because of these feelings, when she died she requested to be buried under a creosote bush in the canyon. Describe below the path of a carbon atom from Grandma Johnson's remains, to inside the leg muscle of a coyote. Be as detailed as you can be about the various molecular forms that the carbon atom might be in as it travels from Grandma Johnson to the coyote. **NOTE:** The coyote does not dig up and consume any part of Grandma Johnson's remains.

Processes = Multiple Process, **Principles** = Tracing Matter, **Scale** = Ecosystem

Interpreting Student Responses: Although there are several ways a student could correctly answer this question, all sophisticated answers require that the student be able to trace carbon in a variety of molecular forms through different pools (e.g. Grandma, soil microbes, atmosphere, plants, herbivores) and processes (e.g. respiration through decomposition, transformation of organic carbon in a coyote). This question assesses how complete/detailed an understanding students have of ecosystem carbon cycling, whether they have misconceptions about processes such as respiration, transformation, and photosynthesis, and whether they have an atomic-molecular understanding of the various forms that carbon can take as it cycles in an ecosystem.

Sample Student Answers:
"Gramma dies, is buried, decomposers consume her, they uptake C, then expel carbon as respired CO2 or as waste. The C is then taken in by plants as CO_2 etc.. A cute little bunny is munching on the plant when a coyote prances, eating the bunny. Through metabolism the C moves into the coyote's blood stream; into the muscle of the leg."
This student makes many trophic connections between the carbon in Grandma Johnson and the coyote. The student does not mention molecular forms of carbon other than carbon dioxide which may indicate an incomplete understanding of transformation of organic carbon to make biomolecules. The student says that C can be taken in by plants as CO_2 etc. which indicates that the student may not know that carbon enters the plant only via photosynthesis and only in the form of carbon dioxide.

"The body will be broken down by decomposers and will be converted into oxygen, which will be used by the coyote and therefore travel inside the leg muscle of the coyote."
This student believes that atoms can be converted to other atoms (carbon can become oxygen).

"When she dies, she will be decomposed by tiny bacteria and fungi. As this happens, carbon is released into the soil, which in turn is taken up by the plant roots as nutrients. The plant in turn gets consumed by a small herbivore, who is then consumed by the coyote."
This student is incorrectly tracing matter from the decomposer to the plant and holds the misconception that plants get their carbon absorbing it through the roots.

2. A loaf of bread was left uncovered for two weeks. Three different kinds of mold grew on it. Assuming that the bread did not dry out, which of the following is a reasonable prediction of the weight of the bread and mold together?

A) The mass has increased, because the mold has grown.
B) The mass remains the same as the mold converts bread into biomass.
C) The mass decreases as the growing mold converts bread into energy.
D) The mass decreases as the mold converts bread into biomass and gases.

Please explain your answer.

When mold grows on the bread, it is actually decomposing the bread and breaking down organic molecules. The carbon in these organic molecules is either converted to carbon dioxide during cellular respiration, or incorporated into the biomass of the mold.

Processes = Respiration, **Principles** = Tracing Matter, **Scale** = Organismal

Interpreting Student Responses: Most students recognize that mass is transferred from the bread to the growing mold. Very few students, however, account for the carbon cost (loss to atmosphere during metabolism) during the process of assimilating bread carbon into biomolecules within the mold. Several students improperly cited "conservation of mass" as a reason why the mold + bread combo would not lose mass.

Students who choose A may recognize that the mold is using the bread as food and that some mass of the mold was in the bread. But, they may also think that the mold is growing by taking in additional molecules from the air. "*As the mold is consuming the bread it is also taking in matter from the air and connecting it into mass*".

Students who choose B are likely not accounting for the carbon cost (loss to the atmosphere during metabolism) during the process of assimilating bread carbon into biomolecules. "*The mold used the bread for energy to grow and the weight of the mold equals the weight of the bread eaten.*"

Students who choose C think that matter can become energy.

Students who choose D are correctly accounting for carbon because they know some of the carbon is assimilated into the mold's biomass, but some of it is respired during the process of growth and maintenance of cells. "*The mass would decrease because the mold uses the bread for nutrients and converts bread into gases as well*"

3. A mature maple tree can have a mass of 1 ton or more (dry biomass, after removing the water), yet it starts from a seed that weighs less than 1 gram. Which of the following processes contributes the most to this huge increase in biomass? Circle the correct answer.

A) absorption of mineral substances from the soil via the roots
B) absorption of organic substances from the soil via the roots
C) incorporation of CO_2 gas from the atmosphere into molecules by green leaves
D) incorporation of H_2O from the soil into molecules by green leaves
E) absorption of solar radiation into the leaf

Processes = Photosynthesis **Principles** = Tracing Matter, **Scale** = Organismal

Interpreting Student Responses: This question asks students to accurately trace the source of mass in a tree. Students must understand the connection between mass gain in a tree and photosynthesis. Students commonly do not see CO_2 as a possible source of mass. Students commonly think that majority of the mass of a plant comes from substances absorbed from the soil (answer choices A, B, and D). Some students think that energy can be converted into matter (answer choice E).

4. Once carbon enters a plant, it can …

A) exit the plant as CO_2. Circle **True** or False
Explain

Cellular respiration occurs in plants, which would result in the loss of carbon dioxide to the atmosphere.

B) become part of the plant cell walls, protein, fat, and DNA. Circle **True** or False
Explain

Glucose is utilized throughout the plant to synthesize various organic molecules, including structural, functional and genetic molecules.

C) be consumed by an insect feeding on the plant and become part of the insect's body. Circle **True** or False
Explain

All parts of a plant contain carbon. An insect obtains its carbon from eating organisms in lower trophic levels, including plants. The carbon molecules that an insect consumes are digested, transported through the body and incorporated into various molecules within the insect.

D) be converted to energy for plant growth. Circle True or **False**
Explain

Matter and energy are coupled, but not interchangeable. The bonds between carbon atoms in a plant contain chemical energy, but carbon atoms cannot be converted to energy.

E) become part of soil organic matter when parts of the plants die and fall off the plant. Circle **True** or False
Explain

Plant parts that enter the soil are generally decomposed by soil organisms. Some of the carbon that was part of the plant enters the atmosphere as carbon dioxide during decomposition, but some of the carbon atoms remain in organic molecules in the soil, which are not decomposed immediately.

Processes = Photosynthesis, Transformation, Respiration **Principles** = Tracing Matter, **Scale** = Organismal

Interpreting Student Responses: This question assesses whether students see multiple fates of carbon within a plant and whether they can accurately trace the path of carbon. Sophisticated answers will include process-based explanations. Choices A, B, and C require an atomic-molecular understanding of carbon transformation (e.g. – molecules are made of atoms, one atom cannot become another, many types of molecules can contain carbon). Choice D might uncover the misconception that matter can be converted to energy.   To reason about choice E, students must know what soil organic matter is and the role of decomposition in the carbon cycle.

5. Coyotes are carnivores. Their bodies include many substances, including proteins in all their cells. What percent of the carbon atoms in a coyote's body were once in the following substances and locations? Fill in the blanks with the appropriate percentages; you may use 0% in your response if you feel it is appropriate. The percentages do not have to add up to 100%.
100 % from CO_2 that was used by plants for photosynthesis
100 % from animals that the coyote ate
0 % from CO_2 that the coyotes inhaled
0 % from inhaling O_2
0 % from soil nutrients that plants absorbed while growing

Please explain your answer.

Coyotes are carnivores, which means they obtain carbon atoms from other animals which are their prey. The carbon atoms in the prey are digested, transported through the blood stream of the coyote and incorporated into tissues. All of the carbon atoms in the prey of the coyote were once carbon dioxide in the atmosphere that was utilized by plants for photosynthesis. Animals in lower trophic levels ate the plants, and the animals were consumed by the coyote.

Processes = Transformation, Respiration, **Principles** = Tracing Matter, **Scale** = Organismal

Interpreting Student Responses: This question assesses whether students can account for the source of the matter in a secondary consumer's body. The question requires that students understand that carnivores do not eat plants, that they get the majority of their mass from eating other animals, that they do no assimilate inhaled CO_2, and that coyotes intake oxygen and water, but that these molecules do not contribute to the majority of their dry biomass.

____% from CO_2 that was used by plants for photosynthesis This % should be high (near 100). A low % indicates the student does not understand that the source of the organic carbon in the food chain is ultimately plants. This student is not tracing matter far enough backward in the food chain.
____% from animals that the coyote ate this % should also be smaller near 100%. If not, students do not understand that the carbon atoms contained in the prey are used for tissue synthesis within the coyote.
____% from CO_2 that the coyotes inhaled this % should be very low. While a tiny % of carbon in the coyote's body might be from CO_2 inhaled along with oxygen, this amount is negligible.
____% from inhaling O_2 If a student puts a number greater than zero, then they are not practicing conservation of matter. O_2 does not contain carbon and oxygen cannot become carbon.
____% from soil nutrients that plants absorbed while growing If a students puts a number greater than zero then they do not understand that the inorganic nutrients that a plant absorbs from the soil while growing are low in mass and do not contain carbon.

6. A potato is left outside and gradually decays. One of the main substances in the potato is the starch amylose ($(C_6H_{10}O_5)_n$). What happens to the atoms in amylose molecules as the potato decays? Choose True (T) or False (F) for each option.

T **F** Some of the atoms are converted into nitrogen and phosphorous: soil nutrients.
T **F** Some of the atoms are consumed and used up by decomposers.
T F Some of the atoms are incorporated into carbon dioxide.

T **F** Some of the atoms are converted into energy by decomposers.

Processes = Respiration, **Principles** = Tracing Matter, **Scale** = Atomic/Molecular

Interpreting Student Responses:
Choice A - If a student chooses "true", then they think an atom can biologically be converted into other type of atom.
Choice B - If a student chooses "true", then they are failing to trace carbon through decomposers. Students often stop accounting for matter when it is transformed from a solid to a gas and are satisfied with vague explanations such as "used up" or "disappears".
Choice D - If a students chooses "true", then they think that matter can be converted to energy.

Trophic Levels DQC's

Tracing carbon is primary key to understanding why mass decreases as trophic levels increase. During each transformation step, matter is converted from organic forms to gaseous forms during cellular respiration. Students who fail to recognize or apply the process of cellular respiration during photosynthesis, herbivory and predation struggle to understand changes in biomass at different trophic levels. **Carbon in Nature** and **Trophic Transfer** are two Diagnostic Question Clusters (DQC's) that can diagnose student understanding of the processes involved mass relationships between trophic levels. Multiple process questions ask students to identify carbon in different trophic levels, and subsequent questions focus on the single processes involved in regulating the mass at different trophic levels. The names of individual questions categorized by process are shown in the table below.

Processes	**Carbon in Nature**	**Trophic Transfer**
Multiple Process	CARBNATOR (1)	TROPMASS (1)
Photosynthesis	FOODMOVE (2), GRASSCO2B (5)	PLANTRESPA (3), FOODMOVE (2)
Transformation – Plant to Plant	FOODMOVE (2)	FOODMOVE (2), 2CARBPATHSB (7b)
Transformation – Plant to Soil		2CARBPATHSD (7d)
Transformation – Plant to Animal	FWFEEDING (4)	FWFEEDING (6), 2CARBPATHSC (7c)
Transformation – Animal to Animal	FWFEEDING (4)	DEERWOLV (5), FWFEEDING (6)
Respiration – Decomposition	DECDIED (3)	
Respiration – Plants	CO2ATM (6)	PLANTRESPA (3), 2CARBPATHSA (7a)
Respiration – Animals	CO2ATM (6)	FAT15 (4)
Combustion	CO2ATM (6)	

Carbon in Nature Diagnostic Question Cluster

An important key to understanding trophic level dynamics, which is a major topic in ecology courses, is correctly locating carbon in various trophic levels. In addition, students must be able to understand how carbon moves between organisms and trophic levels. This diagnostic question cluster begins with a multiple part question asking students to locate carbon in different parts of an ecosystem, and describe how the carbon got to the various places asked about. Subsequent questions follow up on the processes by which carbon is transferred between organisms, and between organic and inorganic sources. Most questions explicitly ask students to reason at an organismal or ecosystem scale, but implicitly include an understanding of molecular level processes.

Carbon in Nature Diagnostic Question Cluster

Please answer the questions below as carefully and completely as you can.

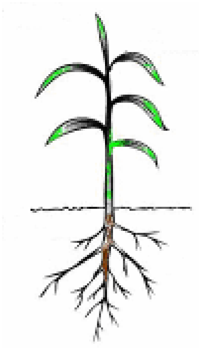
1. Carbon exists in different molecules or substances in nature. Please explain where carbon might exist in a forest.

Question:	YES or NO	If YES, what substances in these locations contain the carbon?	If YES, where did the carbon in these substances come from?
Do you think you would find carbon in trees?	***Yes***	***In biomolecules that make up stems, leaves, phloem, cell walls, etc.***	***Carbon came from the atmosphere via photosynthesis***
Do you think you would find carbon in the soil?	***Yes***	***Decaying organic matter, bodies or bacteria, fungi, animals, plant roots, molecules***	***From dead organisms and body parts that were deposited on the soil, from root exudates***
Do you think you would find carbon in animals, like deer and wolves?	***Yes***	***In biomolecules that make up cell membranes, blood, organs, bone, etc.***	***From the plants and animal flesh that the animal ate***
Do you think you would find carbon in bacteria in the soil?	***Yes***	***In biomolecules like RNA and proteins***	***From the "food" that the bacteria ingested***
Do you think you would find carbon in the air?	***Yes***	***Molecules***	***From respiring organisms, from diffusion from oceans/soils***
Where else you might you find carbon?			

Processes = Photosynthesis, Transformation, Respiration, **Principles** = Tracing Matter, **Scale** = Organismal

Interpreting Student Responses: This question probes whether students understand multiple pools and fluxes within the carbon cycle and that all life contains carbon. Most students think that carbon exists in trees. Some (less than half) mentioned photosynthesis as the process by which it arrived in the tree. Many students only mentioned one or two plant parts where carbon would be found (bark, leaves) and most of the plant parts mentioned were at the organ/macroscopic level rather than the molecular level. Most students thought carbon could be found in soils. They understand that carbon is in dead and decaying plant and animal remains. Students generally think carbon is in animals and can be found throughout the body. Students generally think carbon can be found in the atmosphere. Few cited any carbon containing molecules other than CO_2 that would be found in the atmosphere. When asked what "form" carbon would be in, many students gave vague answers like "air" and "atmosphere"

2. Draw arrows to explain how food moves through a green plant. Explain what the plant's food is, and where it comes from.



Arrows should point downward, from the leaves down to the stem and/or roots.

The plant's food is glucose that is created in the leaves through the process of photosynthesis. The glucose is made from carbon dioxide from the atmosphere and water from the soil, both of which meet in the leaves for the process.

Processes = Photosynthesis, Transformation, **Principles** = Tracing Matter, **Scale** = Organismal

Interpreting Student Responses: In order to answer this question, students need to understand what food is, where it is created, and that food moves from where it is created to where it is used.
Students may provide answers that show they do not understand what food is and that photosynthesis is the process that creates food.

3a. What would happen to the carbon cycle if all decomposers suddenly died and were not replenished? Decide whether each statement is true (T) or false (F).
T F Carbon would accumulate in organic matter.
T **F** There would be more carbon in the soil for plants to absorb.
T **F** Carbon would cycle more rapidly without decomposers.
T **F** Carbon in the atmosphere would increase.

3b. Circle all correct answers. The reason for my responses are that …
A) plants get their carbon from soil through their roots.
B) decomposers serve as a "sink" for carbon and hold it in reserve.
C) with no decomposers the carbon isn't released as CO_2.
D) with one less segment of the food web, carbon would cycle faster.
E) None apply; I wrote my reason to the right of the question.

Processes = Respiration, **Principles** = Tracing Matter, **Scale** = Ecosystem

Interpreting Student Responses: This question assesses student understanding of the role of decomposers in the carbon cycle. To correctly answer, they must trace carbon into and out of decomposers.

Students who think that there would be more carbon in the soil for plants to absorb do not know where carbon enters a plant.
Students who think that carbon would cycle more rapidly without decomposers do not know that decomposers release carbon dioxide to the atmosphere and release nutrients into the soil. Without the decomposers, organisms that die without being eaten by a consumer and waste would remain in its organic form in the soil.
Students who think that carbon in the atmosphere would increase are not accounting for the various processes that remove and replenish carbon dioxide in the atmosphere. Without decomposers, less carbon dioxide would be added.

4. Organisms higher in a food web:
A) eat everything that is lower on the food web.

B) eat organisms directly below them in the food web, but not lower than that.
C) eat only some species directly below them in the food web, but not lower than that.
D) eat only some species directly below them in the food web and some others lower in the food web as well.

Please explain your answer.

Organisms that are higher in the food web often consume many organisms in lower trophic levels, not just in the trophic level immediately below them. For example, a coyote may eat an herbivore such as a rabbit, but may also eat an insect eating bird, which is a carnivore.

Processes = Transformation, **Principles** = Tracing Matter, **Scale** = Ecosystem

Interpreting Student Responses: This question assesses student understanding of food webs. Some students believe that organisms eat only species directly below them on the food web. Some students don't recognize that an organism's diet is restricted by more than just its trophic level.

5. Explain how increased carbon dioxide in the atmosphere might affect the grasses growing on a soccer field.

Processes = Photosynthesis, **Principles** = Tracing Matter, **Scale** = Ecosystem

Interpreting Student Responses: This question requires students to know that photosynthesis is the process by which plants generate organic carbon for growth, that carbon dioxide is a reactant for photosynthesis, and that plants get carbon dioxide from the atmosphere,. Some students may say that atmospheric carbon dioxide doesn't affect plant growth because plants get carbon for photosynthesis from the soil or they may not know that carbon dioxide is a reactant for photosynthesis. Some students may give more sophisticated answers about the mechanism by which increased carbon dioxide affects photosynthesis at that cellular level. Some students may give more sophisticated answers about how increased carbon dioxide could indirectly affect photosynthesis via effects of climate change on the water cycle.

6. Carbon exists in the atmosphere, where could it have come from? Circle all correct answers.

A) Photosynthesis by plants
B) Diffusion from the ocean
C) Cellular respiration by plants
D) Cellular respiration by animals
E) Cellular respiration by bacteria
F) Photosynthesis by fungi
G) Burning of biofuels
H) Burning of fossil fuels
I) Depletion of the ozone layer

Processes = Photosynthesis, Respiration, **Principles** = Tracing Matter, **Scale** = Ecosystem

Interpreting Student Responses: This question assesses whether students understand that carbon enters the atmosphere from a variety of sources and processes. It also assesses whether students have specific omissions/misconceptions about gasses entering and exiting the atmosphere.

A) Student who do not know the correct reactants and products of photosynthesis may think that plants release CO_2 into the atmosphere via photosynthesis.
B) Many students do not recognize that there is gas exchange between the oceans and the atmosphere. This is a topic rarely addressed in introductory texts.
CD) Students who fail to continue to trace carbon after it enters the plant may think that plants and/or animals don't respire.
E) Students think bacteria don't eat or respire. Students commonly do not recognize that the same process that occurs in animals and plants could also occur in single-celled organisms.
F) Students who chose this answer may think that fungi are autotrophs AND that carbon dioxide is a product of photosynthesis.
G/H) The majority of students recognize that burning of fossil fuels releases carbon to the atmosphere, but do not see that biofuels are also a source of carbon in the atmosphere.
I) Some students think that the depletion of the ozone layer is related to the carbon cycle in a direct way. They are not accounting for the specific atoms in ozone. They may not know what ozone is made of or they may think that oxygen can become carbon.

Trophic Transfer Diagnostic Question Cluster

The Tropic Transfer DQC is parallel to the Carbon in Nature DQC, but takes a slightly different angle. Students are asked in question one to provide a reasonable expectation for the mass at various trophic levels. To correctly answer this question, students need to trace matter during herbivory and predation. Specifically, students must correctly identify that carbon is oxidized during aerobic cellular respiration, therefore resulting in decreasing mass as trophic levels increase. Detailed knowledge of molecular scale processes is necessary to piece together the information required to correctly answer the initial ecosystem level question. Wilson et al. (2006) published a slightly different version of question 3 as part of a project to diagnose student ability to trace matter in cell biology systems.

Wilson, C. D., C. W. Anderson, M. Heidemann, J. E. Merrill, B. W. Merritt, G. Richmond, D. F. Sibley and J. M. Parker (2006). "Assessing students' ability to trace matter in dynamic systems in cell biology." Life Sciences Education **5**: 323-331.

Trophic Transfer Diagnostic Question Cluster

Please answer the questions below as carefully and completely as you can.

1. About how much biomass would you expect to find in the herbivores and carnivores in this ecosystem?

Plants ___10,000___kg Herbivores ____________ kg Carnivores ____________ kg

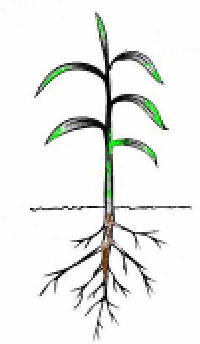
Please explain your answer.

Processes = Multiple Process, **Principles** = Tracing Matter, **Scale** = Ecosystem

Interpreting Student Responses: This question assesses whether students understand most (all but about 10%) of the biomass in one trophic level is respired as carbon dioxide or is eliminated as waste before it is assimilated into the biomass of the next higher trophic level. Some students may simply name a familiar representation such as "food or energy pyramid" or cite that mass decreases as you go up in trophic levels. An answer that includes a model-based explanation, such as biomass is lost to cellular respiration at each level, can be considered more sophisticated.

Some students do not account for a decrease in biomass from one trophic level to the next at all. Some students account for a decrease from plants to herbivores but not for a decrease from herbivores to carnivores. Some students think there is an increase in biomass from one trophic level to the next.

2. Draw arrows to explain how food moves through a green plant. Explain what the plant's food is, and where it comes from.



Arrows should point downward, from the leaves down to the stem and/or roots.

The plant's food is glucose that is created in the leaves through the process of photosynthesis. The glucose is made from carbon dioxide from the atmosphere and water from the soil, both of which meet in the leaves for the process.

Processes = Photosynthesis, Transformation, **Principles** = Tracing Matter, **Scale** = Organismal

Interpreting Student Responses: In order to answer this question, students need to understand what food is, where it is created, and that food moves from where it is created to where it is used. Students may provide answers that show they do not understand what food is and that photosynthesis is the process that creates food.

3. A potted geranium plant sits in a windowsill, absorbing sunlight. After I put this plant in a dark closet for a few days (but keeping it watered), will it weigh more or less (discounting the weight of the water) than before I put it in the closet?

A) It will weigh less because it is still respiring.
B) It will weigh less because no photosynthesis is occurring.
C) It will weigh more because the Calvin cycle reactions continue.
D) It will weigh the same since no biomass is produced.

E) It will weigh more because it still has access to water and soil nutrients.

Processes = Photosynthesis, Oxidation **Principles** = Tracing Matter, **Scale** = Organismal

Interpreting Student Responses: Students must understand that plants gain most of their mass through photosynthesis and lose most of their mass through respiration and transpiration. Students must also understand the effects of light and water availability on the processes of photosynthesis and respiration. Principled reasoning would say that the mass of the plant has to go to or come from somewhere. So B and C are not principled answers—they suggest changes in mass without invoking a process that causes the plant to gain or lose mass. D and E would indicate either that students are not aware that plants respire (about 10% on other questions) or that they discount the weight loss because it is "only" gaseous CO_2 (a far more common problem that also indicates a failure to conserve mass).

4. Your friend lost 15 pounds of fat by dieting. Fat molecules are made from glycerol ($C_3H_5(OH)_3$) and fatty acids such as stearic acid ($C_{17}H_{35}COOH$). What happened to the atoms in the fat molecules when your friend lost weight. Choose True (T) or False (F) for each possibility.

T F Some of the atoms in the fat left your friend's body in carbon dioxide molecules.
T **F** Some of the atoms in the fat left your friend's body in feces.
T **F** Some of the atoms in the fat were converted into energy for body heat and exercise.
T F Some of the atoms in the fat left your friend's body in water molecules.
T **F** Some of the atoms in the fat were burned up when your friend exercised.

Processes = Generation, Oxidation **Principles** = Tracing Matter, **Scale** = Organismal/Atomic-Molecular

Interpreting Student Responses: Students must understand that during metabolism of the fat (in the presence of oxygen), energy that is stored in the fat molecules is used by cells to do work and that carbon dioxide and water will be produced and expelled from the body. Many students think most of the fat leaves the body as feces rather than as carbon dioxide (i.e. – they incorrectly trace matter). Some students think that matter (e.g. fat) can be converted to energy and thus do not understand the principles of conservation of mass and conservation of energy. Some students do not trace matter or energy at all and revert to common phrases such as "burned up" that do not have biological meaning.

5. A remote island in Lake Superior is uninhabited by humans. The primary mammal populations are white-tailed deer and wolves. The island is left undisturbed for many years. Select the best answer(s) below for what will happen to the average populations of the animals over time.

_____a. On average, there will be a few more deer than wolves.
_____b. On average, there will be a few more wolves than deer.
_____c. On average, there will be many more deer than wolves.
_____d. On average, there will be many more wolves than deer.
_____e. On average, the populations of each would be about equal.
_____f. None of the above. My answer would be: ______________________________
____
____

Please explain your answer to what happens to the populations of deer and wolves.

Wolves are carnivores, which mean that they consume herbivores such as deer. Although the wolves kill some deer, there are many more deer than wolves in the ecosystem. If the populations were equal, the wolves would quickly run out of food – as not enough deer would survive to reproduce. In addition, a *small proportion of the matter and energy in a deer is actually transferred to a wolf that eats it; most is lost as carbon dioxide (matter) or heat (energy).*

Processes = Transformation, **Principles** = Tracing Matter, **Scale** = Ecosystem

Interpreting Student Responses: This question contrasts between how students answered #1 above and how the same students answer this question. Many students who recognize the food pyramid pattern in the more conventionally worded #1 fail to recognize it for this question. This is an indicator that their understanding of food pyramids is shallow—something that they recite in response to certain cues—rather than being based on a principled understanding of the necessity of food pyramids: If herbivores and carnivores are both losing biomass through cellular respiration, than there has to be less available for the carnivores.

6. Organisms higher in a food web:

A) eat everything that is lower on the food web.
E) eat organisms directly below them in the food web, but not lower than that.
F) eat only some species directly below them in the food web, but not lower than that.
G) eat only some species directly below them in the food web and some others lower in the food web as well.

Please explain your answer.

Organisms that are higher in the food web often consume many organisms in lower trophic levels, not just in the trophic level immediately below them. For example, a coyote may eat an herbivore such as a rabbit, but may also eat an insect eating bird, which is a carnivore.

Processes = Transformation, **Principles** = Tracing Matter, **Scale** = Ecosystem

Interpreting Student Responses: This question assesses student understanding of food webs. Some students believe that organisms eat only species directly below them on the food web. Some students don't recognize that an organism's diet is restricted by more than just its trophic level.

7. Once carbon enters a plant, it can …

A) exit the plant as CO_2. Circle **True** or False
Explain

Cellular respiration occurs in plants, which would result in the loss of carbon dioxide to the atmosphere.

B) become part of the plant cell walls, protein, fat, and DNA. Circle **True** or False
Explain

Glucose is utilized throughout the plant to synthesize various organic molecules, including structural, functional and genetic molecules.

C) be consumed by an insect feeding on the plant and become part of the insect's body. Circle **True** or False
Explain

All parts of a plant contain carbon. An insect obtains its carbon from eating organisms in lower trophic levels, including plants. The carbon molecules that an insect consumes are digested, transported through the body and incorporated into various molecules within the insect.

D) be converted to energy for plant growth. Circle True or **False**
Explain

Matter and energy are coupled, but not interchangeable. The bonds between carbon atoms in a plant contain chemical energy, but carbon atoms cannot be converted to energy.

E) become part of soil organic matter when parts of the plants die and fall off the plant.
Circle **True** or False
Explain

Plant parts that enter the soil are generally decomposed by soil organisms. Some of the carbon that was part of the plant enters the atmosphere as carbon dioxide during decomposition, but some of the carbon atoms remain in organic molecules in the soil, which are not decomposed immediately.

Processes = Photosynthesis, Transformation, Respiration **Principles** = Tracing Matter, **Scale** = Organismal

Interpreting Student Responses: This question assesses whether students see multiple fates of carbon within a plant and whether they can accurately trace the path of carbon. Sophisticated answers will include process-based explanations. Choices A, B, and C require an atomic-molecular understanding of carbon transformation (e.g. – molecules are made of atoms, one atom cannot become another, many types of molecules can contain carbon). Choice D might uncover the misconception that matter can be converted to energy. To reason about choice E, students must know what soil organic matter is and the role of decomposition in the carbon cycle.

Energy Flow DQC’s

Unlike matter, which cycles within the Earth’s ecosystems, energy flows directionally, entering the Earth’s ecosystems as sunlight and leaving as reflected sunlight or heat. However, energy and matter are coupled, but are not interchangeable; students struggle to understand this relationship. A common misconception is that matter is converted to energy during transformations of organic material, and is often accentuated by phrases commonly used in discussion (e.g. “Cereal at breakfast provides the energy needed for an active day”). Plants capture solar energy and store it as chemical energy within carbon compounds, and most of this chemical energy is lost as heat during cellular respiration. Two Diagnostic Question Clusters (DQC’s), **Energy Pyramid** and **Rainforest** provide parallel questions to diagnose student reasoning about energy flow through ecosystems. Both DQC’s ask students to reason about an ecosystem scale energy flow question, and subsequent questions diagnose their ability to trace energy through individual processes involved in energy flow through ecosystems. The goal is to identify the knowledge gaps, misconceptions and misapplications that prevent students from understanding ecosystem scale questions. The names of individual questions categorized by process are shown in the table below.

Processes	**Energy Pyramid**	**Rainforest**
Multiple Process	ENERPYR1 (1)	TROPFOREST (1)
Photosynthesis	LDTREES(3), CORNGROW (7),	ECOENER1 (2a), WOLVSUN (2b) ENERGYL1 (3), TREEFOREST (6)
Transformation – Plant – Plant	LDTREES (3)	TREEFOREST (6)
Transformation Plant – Animal	GRAPGLUC (4)	ENERGAINA (4a) WOLVSUN (2b)
Transformation – Plant to Decomposer	BREADMOLD (6)	BREADMOLD (5)
Transformation – Energy Loss	ENERPYR3 (2), TROPHERNER (5)	ENERGAINB (4b)
Respiration – Decomposition	BREADMOLD (6), LDTREES (3)	COMPOST (7), BREADMOLD (5)

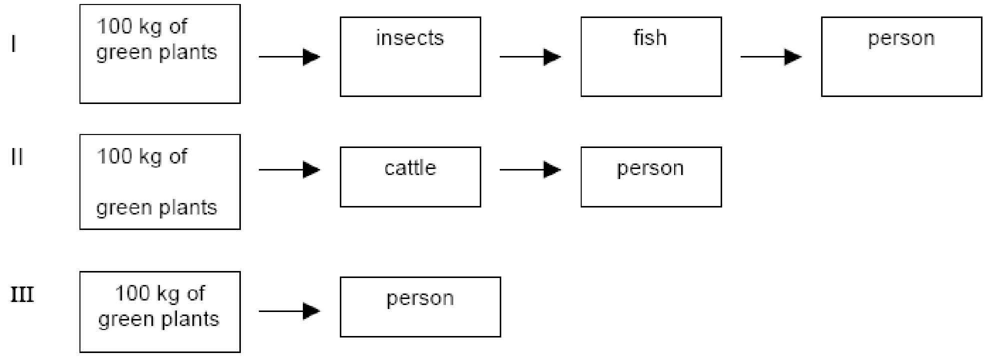
Energy Pyramid Diagnostic Question Cluster

Tracing energy is a necessary principle for understanding ecosystem ecology. Many students incorrectly consider higher trophic levels to contain more energy than lower trophic levels, which is often based on their own experiences consuming vegetables vs. meat products. This DQC specifically asks students to trace energy through trophic levels, and properly identify that energy is lost as heat as matter is transferred within organisms and between trophic levels. Following the initial ecosystem scale, multiple process question, students are asked about processes regarding energy flow, with questions at molecular, organismal and ecosystem scales.

Energy Pyramid Diagnostic Question Cluster

Please answer the questions below as carefully and completely as you can.

1. Consider the three diagrams below. They represent three situations in which 100 kg of green plants serve as the original source of food for each of the food chains. In situation II, for example, cattle eat 100 kg of green plants and then people eat the beef that is produced by the cattle as a result of having eaten the plants.



In which of the three situations is the most energy available to the person?

A) I
B) II
C) III
D) Situations I and II will roughly tie for the most energy.
E) The same amount of energy will be available to the person in all three situations.

Please explain your answer.

As matter is transferred between trophic levels, not only is matter lost to the ecosystem, but energy is also lost as heat. Therefore, the most energy is available to the person in diagram III, where the fewest steps are taken to get to the person.

Processes = Multiple Process, **Principles** = Tracing Matter and Energy, **Scale** = Ecosystem

Interpreting Student Responses: This question requires students to be able to trace matter and energy through an ecosystem and to know that energy is expended as matter is transferred from one trophic level to the next. Students who choose I or II are not effectively tracing matter and/or energy through the ecosystems, and are relying more on their perception of the question based on personal experiences that do not include principled reasoning.

2. A land ecosystem contains grass, grasshoppers, sparrows, and hawks. Which population contains the least energy in the ecosystem?

A) grass
B) grasshoppers
C) sparrows
D) hawks
E) this question does not provide enough information

Please explain your answer.

The hawks are at the top of the food web in this ecosystem, which means that there are fewer hawks than there are sparrows, grasshoppers or grass. As energy is transferred between trophic levels in this ecosystem, energy is lost as heat. Therefore the highest trophic level will contain the least energy.

Processes = Transformation, **Principles** = Tracing Energy, **Scale** = Ecosystem

Interpreting Student Responses: This question requires students to be able to trace matter and energy through an ecosystem and to know that energy is expended as matter is transferred from one trophic level to the next. It also requires students to understand how potential energy is stored by organisms. Many students will choose grass or grasshoppers, simply because of their personal experiences eating food. They understand that plants give them less "energy" than animals when they eat them, so assume that the animals in an ecosystem contain more energy than the plants and herbivores.

3. Does a living tree have energy? **Yes** / No
Does a dead tree have energy? **Yes** / No
Please explain your answers.

Both living and dead trees contain energy in the form of chemical bond energy. When broken, the bonds that hold atoms such as carbon together within the tree release energy for organisms that consume them during cellular respiration. Cells in living trees also respire, thus the energy is used by the tree itself to carry out functions necessary to survive and reproduce.

Processes = Photosynthesis, Respiration, **Principles** = Tracing Energy, **Scale** = Organismal

Interpreting Student Responses:
This question requires students to understand that potential energy is stored in molecules within organisms. When an organism dies, the potential energy stored in biomolecules does not leave the tree until the process of decomposition occurs. Some students think that dead trees do not have energy. These students are not properly applying the principle of conservation of energy.

4. You eat a grape high in glucose content. How could a glucose molecule from the grape provide energy to move your little finger?

A) The glucose is digested into simpler molecules having more energy.
B) The glucose reacts to become ATP (Adenosine Triphosphate).
C) The glucose is converted into energy.
D) The energy of the glucose is transferred to other molecules.
E) The energy of the glucose is transferred to CO_2.and H2O.

Processes = Transformation, **Principles** = Tracing Matter and Energy, **Scale** = Organismal / Atomic-Molecular

Interpreting Student Responses: This question explores whether students understand how chemical potential energy is stored and released through molecular transformations of carbon.. Very few students answer this question correctly, showing us as instructors that they do not understand the flow of energy at an atomic-molecular level. Students who answer A are not properly applying the principle of conservation of energy because they believe one molecule with a certain amount of energy can be broken into molecules that have MORE energy. Students who answered B are not properly tracing matter - they do no know the correct chemical composition of glucose and ATP or they think one atom can become another (e.g. carbon can become phosphorus). Students who answer C think that matter can be converted to energy and do not understand conservation of matter. D is the correct answer. Students who answer E are confused, but know the equation for respiration.

5. The top of a food web:
   A) accumulates all of the energy that existed in the consumed organisms that were lower in the food web.
   B) has less available energy than trophic levels below it.
   C) has the same amount of accumulated energy as each of the trophic levels below it.
   D) has available to it all of the energy of the food web.

Please explain your answer.

As energy is transferred between trophic levels, much of it is lost as heat and leaves the ecosystem. Therefore, the organisms at the top of the food web must have less energy than the trophic levels below them because there is no other way to acquire energy, except by consuming organisms in lower trophic levels (unless it is a plant).

Processes = Transformation, **Principles** = Tracing Energy, **Scale** = Ecosystem

Interpreting Student Responses:
This question requires that students understand that not all energy is transferred from one trophic level to the next because acquiring and assimilating biomolecules requires an expenditure of energy. Many students assume that the top of the food web contains the same amount of energy as levels below them (C), which means that they are incorrectly conserving energy within the ecosystem. Other students assume that higher trophic levels have more energy than lower trophic levels since they are often larger and consumer more animals (A,D).

6. A loaf of bread was left uncovered for two weeks. Three different kinds of mold grew on it. Assuming that the bread did not dry out, which of the following is a reasonable prediction of the weight of the bread and mold together?
   A) The mass has increased, because the mold has grown.
   B) The mass remains the same as the mold converts bread into biomass.
   C) The mass decreases as the growing mold converts bread into energy.
   D) The mass decreases as the mold converts bread into biomass and gases.

Please explain your answer.

When mold grows on the bread, it is actually decomposing the bread and breaking down organic molecules. The carbon in these organic molecules is either converted to carbon dioxide during cellular respiration, or incorporated into the biomass of the mold.

Processes = Respiration, **Principles** = Tracing Matter, **Scale** = Organismal

Interpreting Student Responses: Most students recognize that mass is transferred from the bread to the growing mold. Very few students, however, account for the carbon cost (loss to atmosphere during metabolism) during the process of assimilating bread carbon into biomolecules within the mold. Several students improperly cited "conservation of mass" as a reason why the mold + bread combo would not lose mass.
Students who choose A may recognize that the mold is using the bread as food and that some mass of the mold was in the bread. But, they may also think that the mold is growing by taking in additional

molecules from the air. *"As the mold is consuming the bread it is also taking in matter from the air and connecting it into mass*".

Students who choose B are likely not accounting for the carbon cost (loss to the atmosphere during metabolism) during the process of assimilating bread carbon into biomolecules. *"The mold used the bread for energy to grow and the weight of the mold equals the weight of the bread eaten.*"

Students who choose C think that matter can become energy.

Students who choose D are correctly accounting for carbon because they know some of the carbon is assimilated into the mold's biomass, but some of it is respired during the process of growth and maintenance of cells. *"The mass would decrease because the mold uses the bread for nutrients and converts bread into gases as well*"

7. Each Spring, farmers plant about 5-10 kg of seed corn per acre for commercial corn production. By the fall, this same acre of corn will yield approximately 4-5 metric tons (4,000 – 5,000 kg) of dry, harvested corn. What percent of the mass of the harvested corn was once in the following substances and locations? Fill in the blanks with the appropriate percentages; you may use 0% in your response if you feel it is appropriate.

2.5 % from absorption of mineral substances from the soil via the roots
<1 % from absorption of organic substances from the soil via the roots
95 % from incorporation of CO_2 gas from the atmosphere into molecules by green leaves
2.5 % from incorporation of H_2O from the soil into molecules by green leaves
0 % from absorption of solar radiation into the leaf

Processes = Photosynthesis, **Principles** = Tracing Matter and Energy, **Scale** = Ecosystem

Interpreting Student Responses: Many students can recite and/or write the chemical equation for photosynthesis, but do not properly apply it to questions about mass gain in plants. Most often, students think that mass is gained by absorbing materials through their roots – including carbon based substances. Some students misinterpret the question, not considering only dry biomass, and thus provide a much larger value for water than the correct value. Other students falsely convert energy to matter by supplying a positive value for the last blank.

Rainforest Diagnostic Question Cluster

A large proportion if general biology students assume that both matter and energy are recycled within ecosystems, indicating that students have more trouble tracing energy in ecosystems than matter. The multiple process question at the beginning of this DQC asks students to decide whether matter and energy are recycled within ecosystems, and provide a detailed explanation of their answer. Subsequent questions 2-7 are designed to further diagnose student reasoning about energy flow within ecosystems, and their ability to identify the relationship between matter and energy. Most questions are posed at the scale of the ecosystem, requiring implicit knowledge of molecular processes. Questions three and six ask questions directed more at the molecular scale.

Rainforest Diagnostic Question Cluster

Please answer the questions below as carefully and completely as you can.

1. A tropical rainforest is an example of an ecosystem. Which of the following statements about matter and energy in a tropical rainforest is the most accurate? Please choose ONE answer that you think is best.

A) Energy is recycled, but matter is not recycled.
B) Matter is recycled, but energy is not recycled.
C) Both matter and energy are recycled.
D) Neither matter nor energy are recycled.

Please explain why you think that the answer you chose is better than the others.

Matter is neither created nor destroyed. Within an ecosystem, matter cycles through various biological, chemical and geological forms. Much of the biosphere is made up of carbon atoms, which enter the biosphere through photosynthesis, and leave it through combustion or respiration. Energy, however is not recycled within an ecosystem. Nearly all energy on the planet originates from the sun, and leaves the planet as heat lost to the atmosphere, which is never recaptured by plants, animals or nonliving objects.

Processes = Multiple Process, **Principles** = Tracing Matter and Energy **Scale** = Ecosystem

Interpreting Student Responses: *This question explores student understanding of conservation of matter and energy. It requires students to know that ecosystems are "closed" with respect to matter, but "open" with respect to energy. Students providing answers A or C do not correctly trace energy through ecosystems, not realizing that energy flow is directional instead of cyclical. The opposite is true for matter. Students answer with response A or D, which means that they assume that matter can be created from substances outside of the Earth, possibly from energy.*

2a. What is the ultimate energy source for ecosystems? Please circle the correct answer.

A) nutrients
B) sunlight
C) water
D) carbon
E) carbohydrates
F) others

2b Wolves are nocturnal, meaning that they search for food at night. Therefore, could wolves live without sunlight? Circle Yes or **No**.
Why or why not?

Even though wolves are nocturnal, they still need the sun in order to live. Energy is not recycled within ecosystems, thus a constant supply of energy is required from the sun in order that both plants and higher trophic levels can survive. Wolves rely on photosynthesis by plants and the transfer of energy between plants and herbivores.

Processes = Photosynthesis, Transformation, **Principles** = Tracing Energy, **Scale** = Ecosystem

Interpreting Student Responses: This question requires students to understand that ecosystems are "open" with respect to energy and that sunlight provides the ultimate source of energy for food webs.

Few students will answer part A incorrectly, as they know that sunlight is the primary energy source for the Earth's ecosystems. However, part B tests them to apply this principle by tracing energy from the sun all the way to a carnivore (wolf). Students who answer part B incorrectly may know the textbook answer for where energy comes from, but don't apply it when thinking about ecosystems.

3. Sunlight helps plants to grow. Where does light energy go when it is used by plants? Please choose the ONE answer that you think is best.

A) The light energy is converted into glucose of the plants.
B) The light energy is converted into ATP in the plants.
C) The light energy is used up to power the process of photosynthesis.
D) The light energy becomes chemical bond energy.
E) The light energy does not go into the plants' body.

Processes = Photosynthesis, **Principles** = Tracing Energy, **Scale** = Atomic-Molecular

Interpreting Student Responses: This question explores students' understanding of the role of photosynthesis in converting light energy into chemical bond energy. Students may not understand that principle of conservation of energy and think that energy can be "used up" (C) or that it can be converted into matter (A,B) (e.g. glucose).

4a. Of the energy gained by a plant (i.e. producer), what percentage is typically transferred to a rabbit that eats the plant?

A) 90-100%
B) 60-70%
C) 30-40%
D) 10-20%

4b. If you chose B, C or D, what happens to the energy that does not get transferred between the plant and rabbit?

The energy that is not transferred is lost as chemical bond energy in the feces of the rabbit, or is lost as heat during the process of cellular respiration.

Processes = Transformation, Respiration, **Principles** = Tracing Energy, **Scale** = Ecosystem

Interpreting Student Responses: This question explores whether students can trace energy through a food chain. Students who choose answers A or B do not understand the principles associated with the transfer of energy between organisms. More commonly, students do not know where the energy goes that is lost, commonly citing that it is "used up" or "gone."

5. A loaf of bread was left uncovered for two weeks. Three different kinds of mold grew on it. Assuming that the bread did not dry out, which of the following is a reasonable prediction of the weight of the bread and mold together?

A) The mass has increased, because the mold has grown.
B) The mass remains the same as the mold converts bread into biomass.
C) The mass decreases as the growing mold converts bread into energy.
D) The mass decreases as the mold converts bread into biomass and gases.

Please explain your answer.

When mold grows on the bread, it is actually decomposing the bread and breaking down organic molecules. The carbon in these organic molecules is either converted to carbon dioxide during cellular respiration, or incorporated into the biomass of the mold.

Processes = Respiration, **Principles** = Tracing Matter, **Scale** = Organismal

Interpreting Student Responses: Most students recognize that mass is transferred from the bread to the growing mold. Very few students, however, account for the carbon cost (loss to atmosphere during metabolism) during the process of assimilating bread carbon into biomolecules within the mold. Several students improperly cited "conservation of mass" as a reason why the mold + bread combo would not lose mass.

<u>Students who choose A</u> may recognize that the mold is using the bread as food and that some mass of the mold was in the bread. But, they may also think that the mold is growing by taking in additional molecules from the air. "*As the mold is consuming the bread it is also taking in matter from the air and connecting it into mass*".

<u>Students who choose B</u> are likely not accounting for the carbon cost (loss to the atmosphere during metabolism) during the process of assimilating bread carbon into biomolecules. "*The mold used the bread for energy to grow and the weight of the mold equals the weight of the bread eaten.*"

<u>Students who choose C</u> think that matter can become energy.

<u>Students who choose D</u> are correctly accounting for carbon because they know some of the carbon is assimilated into the mold's biomass, but some of it is respired during the process of growth and maintenance of cells. "*The mass would decrease because the mold uses the bread for nutrients and converts bread into gases as well*"

6. The trees in the rain forest contain molecules of chlorophyll a ($C_{55}H_{72}O_5N_4Mg$). Decide whether each of the following statements is true about the atoms in those molecules. Circle True (T) or False (F).

T F Some of the atoms in the chlorophyll came from carbon dioxide in the air.
T **F** Some of the atoms in the chlorophyll came from sunlight that provided energy for photosynthesis.
T F Some of the atoms in the chlorophyll came from water in the soil.
T F Some of the atoms in the chlorophyll came from nutrients in the soil.
T F Some of the atoms in the chlorophyll came from glucose produced by photosynthesis
T F Some of the atoms in the chlorophyll came from the seed that the tree grew from.

Processes = Photosynthesis, Transformation, **Principles** = Tracing Matter, **Scale** = Atomic-Molecular

Interpreting Student Responses: This question asks students to accurately trace molecules of chlorophyll back to their entry into the plant. Some students think that energy can become matter and vice versa (2nd Response). Some students do not believe that plants get CO2 for photosynthesis from the air. Hydrogen atoms in the water are incorporated into glucose during photosynthesis, and the glucose is utilized in the synthesis of other molecules, such as chlorophyll. The seed and the soil also provide minerals such as nitrogen that are in the chlorophyll. Most importantly, students must be able to trace particular atoms from their source to their sink within the chlorophyll molecule, which is difficult at an atomic-molecular scale.

7. When the leaves in a compost pile decay, they lose mass. What do you think happens to the mass of the leaves? Circle True (T) or False (F).

T **F** The mass goes away when the leaves decompose.
T **F** The mass is converted to heat energy.
T F The mass is converted into soil minerals.

T F The mass is converted into carbon dioxide and water.
Please explain your answers.

The matter in the dead leaves is decomposed by organisms in the compost pile. The carbon and hydrogen in the organic substances (along with oxygen from the air) is converted to carbon dioxide and water. The minerals in the leaves are not respired, but are liberated from the organic compounds and remain in the soil.

Processes = Respiration, **Principles** = Tracing Matter, **Scale** = Organismal

Interpreting Student Responses: This question asks student to properly trace matter through the process of decomposition. Many students do not realize that decomposition involves respiring microbes that take in carbon compounds from dead organisms and release CO_2 and water primarily. Some atoms are also mineralized during decomposition and released into the soil in a non-gaseous form, such as phosphorus.

Understanding Climate Change DQC's

What knowledge does a student, or citizen, need in order to understand a scientific document about climate change, such as the reports published by the Intergovernmental Panel on Climate Change? In addition to understanding the scientific method, students must decipher the complex chemical, biological and physical processes involved in the accumulation of atmospheric greenhouse gases and the ability of those gases to absorb infrared radiation reflected from the Earth's surface back towards the atmosphere. At the heart of understanding this complexity is tracing matter, particularly carbon, and tracing energy associated with carbon containing molecules. **Carbon Balance** and **Keeling Curve** are two parallel Diagnostic Question Clusters (DQC's) that are intended to diagnose problems in student reasoning about the processes involved in global climate change. Following an initial multiple process question, students are asked about individual processes contributing to the multiple process question. The names of individual questions categorized by process are shown in the table below.

Processes	**Carbon Balance**	**Keeling Curve**
Multiple Process	ATMBALANCE (1)	KLGSEASON (1)
Photosynthesis	FOODMOVE (3)	CORNGROW (3)
Transformation – Plant to Soil	ORIGFUEL (4), FALEAVEA (5a)	FALEAVEA (4a)
Respiration – Decomposition	FALEAVEA (5a), FALEAVEB (5a)	FALEAVEA (4a), FALEAVEB (4b)
Combustion	COALELEC (6)	QANGASCO (5)
Atmosphere – Greenhouse effect	GLOBWAMC (2)	EARTHWARM (6)
Biogeography		GLOBELAND (2)

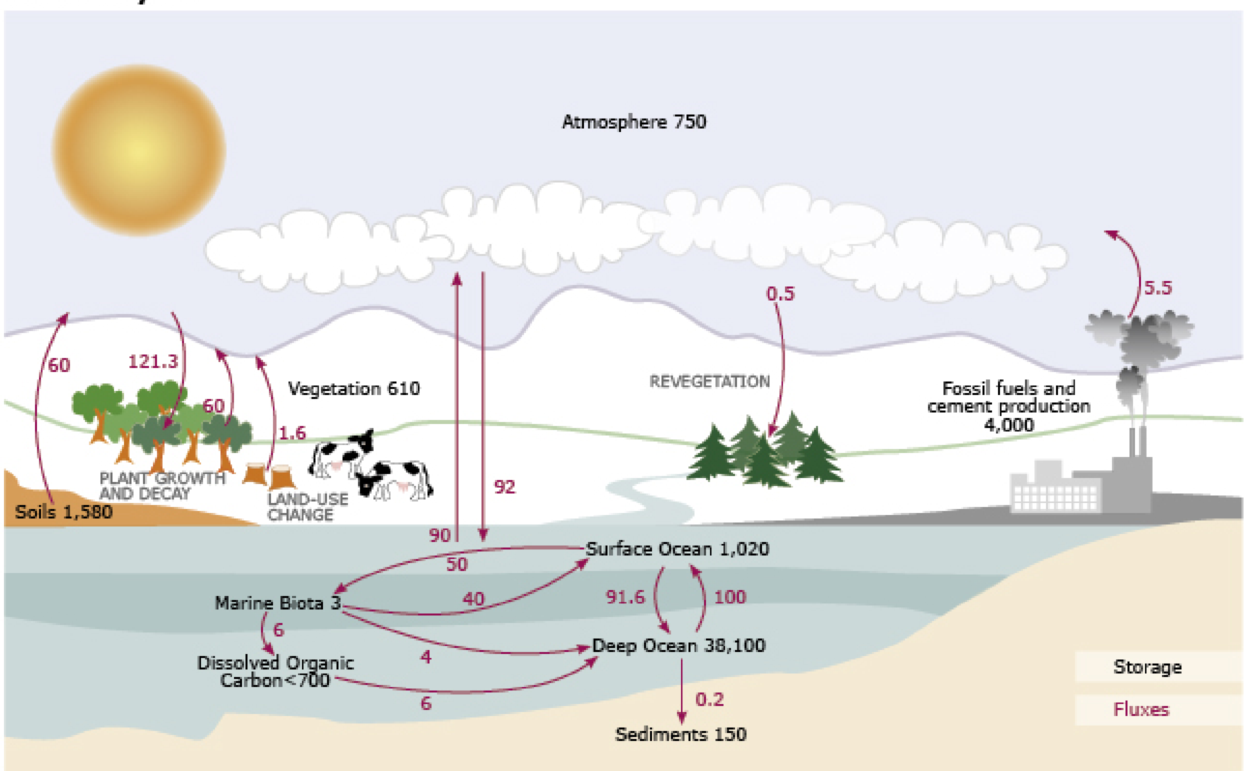
Carbon Balance Diagnostic Question Cluster

Human activities have caused an imbalance in the carbon cycle; most notable is the increase in atmospheric carbon dioxide. However, the rate at which carbon dioxide accumulates in the atmosphere depends on many other carbon transformation processes. In this DQC, students are asked to interpret a carbon cycle diagram that is out of balance; more carbon dioxide is entering the atmosphere than is leaving the atmosphere. Single process questions (2-6) that follow question one require students to individually trace matter through several different carbon transformations. These individual processes are imperative for understanding and explaining the larger imbalance in the global carbon cycle. At the ecosystem scale, students must reconcile human influences to the carbon cycle with ongoing carbon transformation processes occurring with or without human involvement, all the while applying their knowledge of processes that occur at the organismal and molecular levels.

Carbon Balance Diagnostic Question Cluster

Please answer the questions below as carefully and completely as you can.

The carbon cycle diagram shown below indicates the Earth's carbon pools and fluxes. The units used for pools are Pedagrams (10^{15} grams), and the fluxes are in Pedagrams per year.



1. Based on the diagram above, is atmospheric carbon at a steady state? Circle Yes or **No**.
Please explain your answer.

There is more carbon entering the atmosphere (217.1 Pg/year) than leaving the atmosphere (213.8 Pg/year). This appears to be a small difference, but a Pedagram is a very large unit, the same as 10^{15} *grams. Fossil fuel burning and cement production, along with land use change are sources of additional carbon dioxide emissions to the atmosphere. Extra plant growth on land and in the ocean, as well as carbon dioxide diffusion into the ocean remove some of the excess carbon dioxide from the atmosphere, but not all of it.*

Processes = Multiple Process, **Principles**: = Tracing Matter, **Scale =** Ecosystem

Interpreting Student Responses: This question assesses whether students can read a pool and flux diagram and whether they understand the meaning of "steady state," as well as explaining the current imbalance in the global carbon cycle due to human activities. Students often struggle to interpret carbon cycle diagrams, limiting their understanding of the processes involved in carbon fluxes and pools. Students misinterpreting this diagram can be further diagnosed using the single process questions below.

2. Scientists believe that the average temperature of the earth's atmosphere has been increasing

during the past 100 years. What is the major cause of this?

A) More heat is released from vehicles and factories into the atmosphere.
B) More particulate pollution (smog) is in the atmosphere.
C) More carbon dioxide is in the atmosphere.
D) Deterioration of the ozone layer
E) None of these causes global warming.

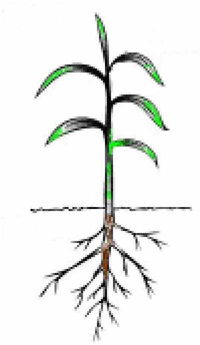
Please explain your answer.

Carbon dioxide is a greenhouse gas, which traps heat in the Earth's atmosphere by absorbing specific infrared wavelengths that would otherwise continue to pass through the atmosphere, back into space. Human activities have substantially increased the amount of carbon dioxide in the atmosphere, which has caused a significant increase in average Earth surface temperatures.

Processes = Greenhouse Effect, **Principles** = Tracing Matter and Energy, **Scale** = Ecosystem

Interpreting Student Responses: Students must understand the process by which climate change is occurring, as biofuel combustion results in carbon dioxide released to the atmosphere, which traps heat near the Earth's surface. Many students attribute climate change to the depletion of the ozone layer. All responses are chosen by students at varying frequencies.

3. Draw arrows to explain how food moves through a green plant. Explain what the plant's food is, and where it comes from.



Arrows should point downward, from the leaves down to the stem and/or roots. The plant's food is glucose that is created in the leaves through the process of photosynthesis. The glucose is made from carbon dioxide from the atmosphere and water from the soil, both of which meet in the leaves for the process.

Processes = Photosynthesis, Transformation, **Principles** = Tracing Matter, **Scale** = Organismal

Interpreting Student Responses: In order to answer this question, students need to understand what food is, where it is created, and that food moves from where it is created to where it is used. Students may provide answers that show they do not understand what food is and that photosynthesis is the process that creates food.

4. Coal, oil, and gas are called fossil fuels. What were they before they became fossil fuels?

Before becoming fossil fuels, these substances were living plants millions of years ago. These plants died and were protected from decomposition by various factors, Instead of being decomposed, the dead plants were compressed within the Earth and the process converted them into the fossil fuels we have today.

Processes = Photosynthesis, Transformation, **Principles** = Tracing Matter, **Scale** = Ecosystem

Interpreting Student Responses: This question assesses whether students understand the remains of ancient plants are the source of fossil fuel, and that those plants obtained their carbon from carbon dioxide in the atmosphere. Students often think that prehistoric animals and plants were "decomposed" into fossil fuels, which shows that they have troubles tracing matter through time, as decomposition would cause the carbon atoms to be released to the atmosphere.

5a. In the fall, the leaves on trees in a deciduous forest fall to the ground. Explain what happens to the leaves once they fall to the ground.

The leaves are decomposed by soil organisms. The matter in the leaves is lost as carbon dioxide and water as the decomposers break down the organic substances in the leaves.

5b. Do the changes in the dead leaves affect atmospheric carbon dioxide levels? Circle **Yes** or No. Why or why not?

Plants absorb carbon dioxide from the atmosphere during photosynthesis, thus removing carbon dioxide from the atmosphere. Decomposers that break down the leaves release carbon dioxide to the atmosphere, thus increasing carbon dioxide levels back to where they were before the plant produced the leaves.

Processes = Respiration, Transformation, **Principles** = Tracing Matter, **Scale** = Organismal

Interpreting Student Responses: Part A of the question assesses whether students understand that decomposers use discarded plant tissue as a source of carbon and energy. Part B assesses whether students see a link between decomposition and atmospheric carbon dioxide. A matter-tracing answer to Part A would follow the carbon, hydrogen, oxygen, and other elements into CO2, H2O, and soil minerals. Part B would then be redundant. Note, though, how different the students' answers to Parts a and b tend to be. Part a responses mention the leaves going into the soil or energy, but not CO2. Part B responses that mention decomposition releasing CO2 still often fail to mention the origins of the carbon.

Most students think that leaves will decompose. Some students have difficulty seeing a link between decomposition of the dead leaves in the soil and atmospheric gasses, specifically CO_2.

6. Power plants often burn coal to produce electricity. Where do the atoms in the coal go when it is burned? Decide whether each of the statements below is true (T) or false (F).

T F Some of the mass of the coal produces carbon dioxide in the atmosphere.
T **F** Some of the mass of the coal produces sulfuric acid in the atmosphere.
T **F** Some of the mass of the coal is converted to heat and electrical energy.
T **F** Some of the mass of the coal produces oxygen in the atmosphere.
T **F** Some of the mass of the coal is consumed by the flame when it is burned.

Processes = Combustion, **Principles** = Tracing Matter, **Scale** = Atomic-Molecular

Interpreting Student Responses: This question assesses whether students know that coal is made of carbon atoms and that during combustion, the molecules within coal are rearranged to form different molecules. Students may have difficulty tracing matter during its conversion from one form to another ("produces sulfuric acid"), may not trace matter at all ("consumed by the flame"), or may think that matter can be converted to energy ("coal is converted into heat energy")

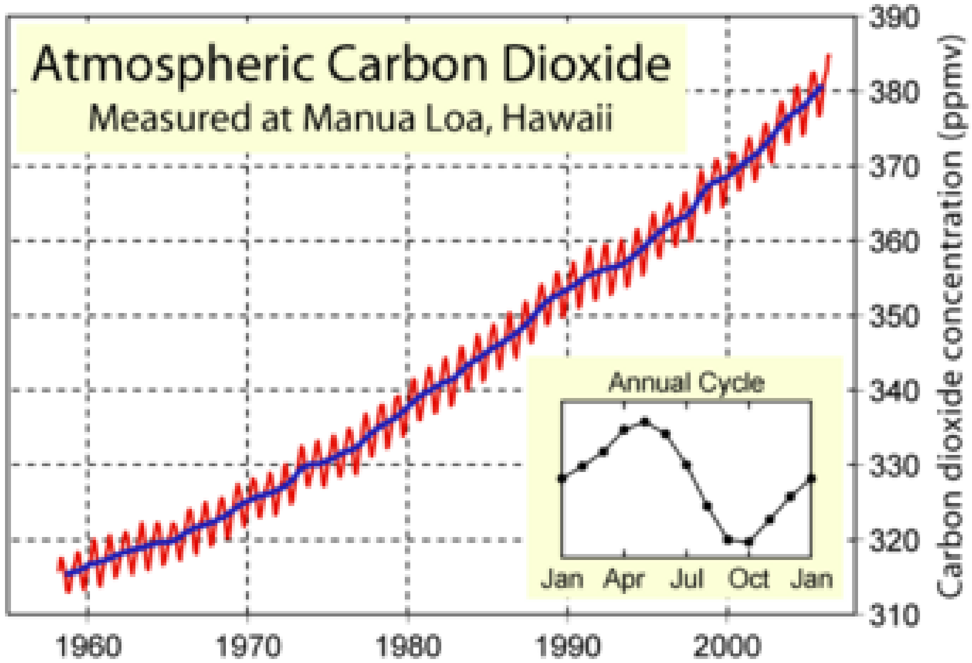
Keeling Curve Diagnostic Question Cluster

The Keeling Curve is a diagram that shows data collected on carbon dioxide levels at Mauna Loa, Hawaii, starting in the 1950's. This diagram shows increasing carbon dioxide levels across years, but fluctuating levels within years due to changes in photosynthesis and respiration across seasons. Students are asked to interpret this diagram, describing both the changing levels over multiple years and changes within a single season. In addition to the carbon transformation processes that must be understood to interpret the Keeling Curve (questions 3-5), students must also have an understanding of biogeography, that the majority of land mass is located in the Northern Hemisphere (question 2). Without hemisphere differences, intra-annual fluctuations would not be evident. This DQC poses questions to students at the ecosystem scale, including questions about human influences, but requires an implicit understanding of smaller scale processes, some of which are asked about in questions two through five.

Keeling Curve Diagnostic Question Cluster

Please answer the questions below as carefully and completely as you can.

1. The graph given below shows changes in concentration of carbon dioxide in the atmosphere over a 47-year span at Mauna Loa observatory at Hawaii.



1a. Why do you think this graph shows atmospheric carbon dioxide levels decreasing in the summer and fall and carbon dioxide levels increasing in the winter and spring?

The graph shows these intra-annual oscillations because of the balance between photosynthesis and respiration by organisms on Earth. During the summer in the Northern Hemisphere, plants are growing, photosynthesizing, and taking carbon dioxide out of the atmosphere. In the winter, plants are not growing, and photosynthesize, but plants, animals, microbes and other organisms are still respiring, thus releasing carbon dioxide to the atmosphere.

1b. Why do you think the levels of carbon dioxide have increased from 1960 to present?

Human activities such as the combustion of fossil fuels and land use change have resulted in large amounts of carbon dioxide released to the atmosphere. These activities continue year after year, causing the increase in atmospheric carbon dioxide levels over time.

Processes = Multiple Process, **Principles** = Tracing Matter, **Scale** = Ecosystem

Interpreting Student Responses: This question asks students to reason about two phenomena 1) the increase of atmospheric carbon dioxide over the last 60 years due to the burning of fossil fuels that had been stored beneath the Earth's surface, 2) the annual oscillation of CO_2 due to seasonality of the balance of photosynthesis and respiration in plant, 3) that although CO2 is relatively well mixed in the atmosphere, local sources of CO2 emissions can result in "noise" in the data set.

For part A, students struggle to provide responses that aren't centered on human dimensions, but instead incorporate the differences between photosynthesis and respiration at different times of the year. Many answer focus on the amount of fossil fuel use for driving and/or heating homes. For part B, more students realize the excess carbon dioxide being emitted from human activities. Still, some attribute the sharp rise to volcanic activity or natural cycles.

2. Would you expect to find more living plant mass in the Northern or Southern Hemisphere of the Earth? Please explain why you chose your answer.

Northern Hemisphere. There is more land in the Northern Hemisphere compared to the Southern Hemisphere, and both hemisphere's receive equal amounts of sunlight and relatively equal amounts of precipitation.

Processes = Biogeography **Principles** = Tracing Matter, **Scale** = Ecosystem

Interpreting Student Responses: Although this question doesn't fall under our matter and energy framework, it is important in understanding the dynamics of the Keeling Curve. Students who don't understand biogeography (that more plant mass exists in the Northern Hemisphere) will have a difficult time answering part A of question 1.

3. Each Spring, farmers plant about 5-10 kg of seed corn per acre for commercial corn production. By the fall, this same acre of corn will yield approximately 4-5 metric tons (4,000 – 5,000 kg) of dry, harvested corn. What percent of the mass of the harvested corn was once in the following substances and locations? Fill in the blanks with the appropriate percentages; you may use 0% in your response if you feel it is appropriate.

2.5 % from absorption of mineral substances from the soil via the roots
<1 % from absorption of organic substances from the soil via the roots
95 % from incorporation of CO_2 gas from the atmosphere into molecules by green leaves
2.5 % from incorporation of H_2O from the soil into molecules by green leaves
0 % from absorption of solar radiation into the leaf

Processes = Photosynthesis, **Principles** = Tracing Matter and Energy, **Scale** = Ecosystem

Interpreting Student Responses: Many students can recite and/or write the chemical equation for photosynthesis, but do not properly apply it to questions about mass gain in plants. Most often, students think that mass is gained by absorbing materials through their roots – including carbon based substances. Some students misinterpret the question, not considering only dry biomass, and thus provide a much larger value for water than the correct value. Other students falsely convert energy to matter by supplying a positive value for the last blank.

4a. In the fall, the leaves on trees in a deciduous forest fall to the ground. Explain what happens to the leaves once they fall to the ground.

The leaves are decomposed by soil organisms. The matter in the leaves is lost as carbon dioxide and water as the decomposers break down the organic substances in the leaves.

4b. Do the changes in the dead leaves affect atmospheric carbon dioxide levels? Circle **Yes** or No. Why or why not?

Plants absorb carbon dioxide from the atmosphere during photosynthesis, thus removing carbon dioxide from the atmosphere. Decomposers that break down the leaves release carbon dioxide to the atmosphere, thus increasing carbon dioxide levels back to where they were before the plant produced the leaves.

Processes = Respiration, Transformation, **Principles** = Tracing Matter, **Scale** = Organismal

Interpreting Student Responses: Part A of the question assesses whether students understand that decomposers use discarded plant tissue as a source of carbon and energy. Part B assesses whether students see a link between decomposition and atmospheric carbon dioxide. A matter-tracing answer to Part A would follow the carbon, hydrogen, oxygen, and other elements into CO2, H2O, and soil minerals. Part B would then be redundant. Note, though, how different the students' answers to Parts a and b tend to be. Part a responses mention the leaves going into the soil or energy, but not CO2. Part B responses that mention decomposition releasing CO2 still often fail to mention the origins of the carbon.

Most students think that leaves will decompose. Some students have difficulty seeing a link between decomposition of the dead leaves in the soil and atmospheric gasses, specifically CO_2.

5a. Do you think the following statement can be correct? Circle **Yes** or No.
One gallon of gasoline, which weighs about 6.3 pounds, could produce 20 pounds of carbon dioxide when burned.

5b. Explain your reasoning. How could the carbon dioxide weigh more than the gasoline, or why is this impossible? (Note: Gasoline is a mixture of hydrocarbons such as octane: C_8H_{18}.)

During combustion, gasoline is not the only reactant in the equation. Oxygen in the atmosphere is another reactant. The oxygen is combined with carbon atoms in the octane to produce carbon dioxide, which is released to the atmosphere. The hydrogen atoms in the octane are incorporated into water molecules, but the hydrogen atoms have little mass compared to carbon and oxygen.

Processes = Combustion, **Principles** = Tracing Matter, **Scale** = Atomic-Molecular

Interpreting Student Responses: This question assesses whether students have an atomic-molecular understanding of fossil fuel combustion. In order to correctly answer the question, students must know the reactants and products of the equation and that atoms have different weights, so molecules have different weights. Unprincipled thinking could result in a "No" answer, accompanied by an explanation that fails to incorporate all reactants in the combustion process, or fails to trace matter through the process.

Carbon Dynamics in Energy Production DQC's

Fossil fuel combustion is one of the major causes of increased carbon dioxide levels in the atmosphere. However, the accumulation of atmospheric carbon dioxide due to this combustion process is not as simple as it would appear, as the carbon atoms in gasoline were stored in locations not available for decomposition. Although biofuel combustion is the same process as fossil fuel combustion, biofuel combustion does not theoretically result in increased atmospheric carbon dioxide levels. The carbon transformation processes that lead to the "old" carbon in gasoline and the "new" carbon in biofuels are essential for reasoning about the outcomes of combustion. The two Diagnostic Question Clusters (DQC's) in this topic, **Biofuels** and **Gasoline**, intend to diagnose problematic student thinking about generation and combustion of these two transportation fuels, identifying the important processes involved that students fail to comprehend. The names of individual questions categorized by process are shown in the table below.

Processes	**Biofuels**	**Gasoline**
Multiple Process	BIOFUEL (1)	GASTRACE (1)
Photosynthesis	CARBRESB (3b), CORNGROW (7)	CARBRESB (3b), GASENMATTC (4c)
Transformation – Plant to Soil	SOILCLOSS1 (6a), SOILCLOSS3 (6c), SOILCLOSS4 (6d)	GASENMATTC (4c)
Respiration – Decomposition	SOILCLOSS2 (6b), SOILCLOSS3 (6c)	GASDECOMPA (7a)
Combustion	BIOCOMBUST (5)	OCTANE (2), ENERMTCH (5), GASDECOMPB (7b), GASENMATTA (4a), GASENMATTB (4b), GASENMATTD (4d)
Greenhouse Effect	GLOBWAMC (2)	EARTHWARM (6),
Carbon Residency Time	CARBRESA (3a)	CARBRESA (3a)
Biofuel Production	BIOFUEL2 (4)	

Biofuels Diagnostic Question Cluster

Biofuels are considered to be a source of transportation fuel that can help to reduce the need for fossil fuels, and reduce the rate at which greenhouse gases are accumulating in the atmosphere. In order to understand why biofuels theoretically do not contribute excess carbon dioxide to the atmosphere, students must have a detailed understanding of carbon transformations involved in producing biofuels, particularly the process of photosynthesis. Instead of citing the differences in origin of carbon in biofuels and fossil fuels, students assume that biofuel combustion does not result in the release of carbon dioxide. Question one in this DQC asks students to explain why utilization of biofuels would theoretically reduce the rate of global climate change, while subsequent questions dig deeper into the processes, such as photosynthesis and the greenhouse effect, that are involved in answering the first question. These single process questions aid in pinpointing the knowledge gaps in student understanding about the benefits and consequences of biofuel production and use for transportation.

Biofuels Diagnostic Question Cluster

Please answer the questions below as carefully and completely as you can.

1. Explain why the use of biofuels instead of fossil fuels is a strategy to slow the rate of global climate change. Use as much detail in your answer as you can.

Biofuels are made from plants that were recently grown. Both biofuels and fossil fuels are converted to carbon dioxide when combusted, but the carbon that is contained in biofuels was recently converted to organic carbon through photosynthesis, and would have been returned to the atmosphere via decomposition of the plant material anyway. Thus, burning biofuels contributes no net increase in atmospheric carbon dioxide levels, which are the primary cause of climate change. The carbon contained in fossil fuels has been located in solid form in the Earth for millions of years, and would not be expected to be converted to carbon dioxide by natural processes. Therefore, burning fossil fuels does result in a net increase in atmospheric carbon dioxide levels.

Processes = Multiple Processes, **Principles** = Tracing Matter and Energy, **Scale** = Ecosystem

Interpreting Student Responses: In order to explain why biofuels are considered to reduce the effects of climate change, students need to understand several processes about carbon cycling, particularly that the carbon dioxide released during biofuel combustion was recently taken out of the atmosphere via photosynthesis, whereas fossil fuels have been located in the ground for millions of years and would not be released to the atmosphere without human intervention. Students A) think that biofuels result in less carbon dioxide emissions than fossil fuels when burned, failing to trace carbon during combustion, B) say that biofuels don't give off greenhouse gases at all, (similar reasoning to A), C) Fail to recognize the age of organic carbon in biofuels and fossil fuels, D) confuse the greenhouse effect with the ozone layer.

2. Scientists believe that the average temperature of the earth's atmosphere has been increasing during the past 100 years. What is the major cause of this?

A) More heat is released from vehicles and factories into the atmosphere.
B) More particulate pollution (smog) is in the atmosphere.
C) More carbon dioxide is in the atmosphere.
D) Deterioration of the ozone layer
E) None of these causes global warming.

Processes = Greenhouse Effect, **Principles** = Tracing Matter and Energy, **Scale** = Ecosystem

Interpreting Student Responses: Students must understand the process by which climate change is occurring, as biofuel combustion results in carbon dioxide released to the atmosphere, which traps heat near the Earth's surface. Many students attribute climate change to the depletion of the ozone layer. All responses are chosen by students at varying frequencies.

3a. On average, how long do you think a molecule of carbon dioxide remains in the atmosphere after being released by a human being?

Anywhere between 2 and 20 years would be considered appropriate answers. Five – ten years is considered to be the average residence time for CO_2 *in the atmosphere.*

Processes = Carbon Residency Time, **Principles** = Tracing Matter, **Scale** = Atomic-Molecular, Ecosystem

Interpreting Student Responses: The major reason for asking this question is to lead into question 3b. However, students don't tend to recognize how long a molecule of carbon dioxide remains in the atmosphere before being transformed to organic carbon through photosynthesis or dissolving into a water body. In multiple choice format, students tend to choose either a 5 year, 50 year, or 350 million year residence time. Students providing very long time frames don't appear to understand the path that carbon takes between the biosphere and atmosphere.

3b. After a period of time, the carbon atom released by a human being will leave the atmosphere. Where does the carbon atom go when it leaves the atmosphere?

Carbon in the atmosphere is in the form of carbon dioxide. It leaves the atmosphere when a plant utilizes the molecule of carbon dioxide in photosynthesis. During this process, carbon dioxide is combined with water to form glucose, an organic carbon molecule.

Processes = Photosynthesis, **Principles** = Tracing Matter, **Scale** = Atomic-Molecular, Ecosystem

Interpreting Student Responses: This question specifically asks students to recognize the process of photosynthesis without being explicitly asked about photosynthesis. Students may respond with answers that say carbon escapes the atmosphere, which incorrectly conserves matter. They may also say it is incorporated into animals during breathing, or dissolved into the Earth. They may also respond with an alternative correct answer that carbon dioxide dissolves into water bodies, and is converted to carbonate molecules, but this is unlikely unless they have learned this process.

4. What are biofuels? How are they different from fossil fuels?

Biofuels are combustible materials stored in liquid form that release large amounts of energy when burned. Most often, these materials are specifically made from plant tissues, which are fermented and distilled to produce combustible alcohols such as ethanol. Fossil fuels are formed from plant materials also, but are converted into hydrocarbons through millions of years of pressure within the Earth.

Processes = Biofuel Production, **Principles** = Tracing Matter and Energy, **Scale** = Ecosystem

Interpreting Student Responses: If students don't understand what biofuels are – and how they are different from fossil fuels, they cannot understand why biofuels theoretically would reduce the rate of climate change. Students may understand principles of carbon cycling, but may lack understanding of what biofuels are. Students commonly infer that the matter in plants is converted to energy. They also often provide partially correct, but incomplete answers, such as biofuels are "corn gas."

5. Liquid biofuels are mostly a mixture of hydrocarbons, such as ethanol (C_2H_6). Decide whether each of the following statements is true (T) or false (F) about what happens to the atoms in a molecule of ethanol when it burns.

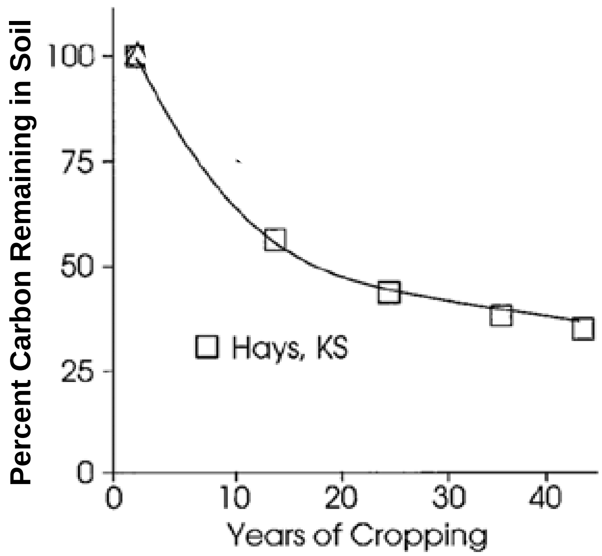
T F Some of the atoms in the ethanol are incorporated into carbon dioxide in the air.
T **F** Some of the atoms in the ethanol are incorporated into air pollutants such as ozone or nitric oxide.
T **F** Some of the atoms in the ethanol are converted into energy that moves the car.
T **F** Some of the atoms in the ethanol are burned up and disappear.

T **F** Some of the atoms in the ethanol are converted into heat.
T F Some of the atoms in the ethanol are incorporated into water vapor in the atmosphere.

Processes = Combustion, **Principles** = Tracing Matter and Energy, **Scale** = Atomic-Molecular

Interpreting Student Responses: Biofuels are combusted to release heat energy which is converted to mechanical energy. However, many students believe that biofuel combustion results in fewer emissions than fossil fuel combustion, or zero emissions. Therefore, they don't trace matter effectively, often because they convert matter to energy. We ask the same question about octane from gasoline in the Gasoline DQC, question 2. Incorrect student responses are found for all six true/false questions. Most commonly, students incorrectly convert matter to energy.

6. The figure below shows the percent of carbon remaining in the soil during the first 40 years of growing crops in a prairie region near Hays, Kansas.



6a. How did carbon get into the soil before crops were grown?

Soil carbon comes from the process by which organic matter from plants and animals is decomposed in soil, resulting in respiration of most of the carbon, but some smaller pieces of organic matter remain in the soil. The carbon in the plants and animals was recently in the form of carbon dioxide, but was transformed into organic molecules through photosynthesis.

Processes = Transformation, **Principles** = Tracing Matter, **Scale** = Ecosystem

Interpreting Student Responses: Theoretically, using crops to produce biofuels should result in a net reduction in greenhouse gas emissions. However, cultivation impacts soil carbon as well as producing biomass from crops. This series of questions is designed to assess student understanding of tracing matter between plants, soil and the atmosphere, and how producing biofuels has some unintended consequences related to climate change. Specifically, question 6a is intended to assess student understanding of the process by which soils accumulate organic carbon.Incorrect student responses include the carbon came directly from the atmosphere by falling, came from rain and that burning dead plants was responsible for the carbon (not incorrect, but not the major source).

6b. The percent of carbon remaining in soil decreased over time. Where did it go?

The carbon in soil is in an organic form. Decomposers utilize the chemical bond energy in organic carbon during cellular respiration. Subsequently, the carbon atoms in the organic matter are converted to carbon dioxide, and are released to the atmosphere.

Processes = Respiration, **Principles** = Tracing Matter, **Scale** = Ecosystem

Interpreting Student Responses: This question specifically asks students about cellular respiration by decomposers, and that this process releases CO_2 to the atmosphere. The most common incorrect response is that carbon is taken up by plants and stored within the plant, which fails to recognize respiration during decomposition and incorrectly characterizes carbon movement during photosynthesis.

6c. If farmers continued to grow crops for more than 40 years, do you think the percent of soil carbon would eventually reach zero? Why or why not?

No, not all of the crop plant is harvested by farmers, especially the roots which remain in the soil. The dead plant material is decomposed over time and carbon is released as carbon dioxide, but organic matter inputs yearly from crop residue ensure that soil organic carbon will never reach zero.

Processes = Transformation, Respiration, **Principles** = Tracing Matter, **Scale** = Ecosystem

Interpreting Student Responses: This question assesses student ability to trace carbon from plant material to soil organic matter. This question helps to assess if students understand why the graph levels off at a certain point that continues crop residue is continually incorporated into the soil organic matter pool. Students that say “yes”, commonly say that the crop is using more carbon than it can put back into the soil. Some students that say “no” often reason that some force is maintaining a small amount of carbon in the soil that some carbon in soil is “needed” to maintain life, so it couldn’t get to zero.

6d. Scientists would suggest that carbon in the soil would increase if farmers stopped growing crops. Why would this increase in soil carbon occur?

Crop harvest results in the removal of organic matter from the ecosystem, which reduces the amount of carbon entering the soil. In addition, cultivation processes enhance decomposition of soil organic matter, which releases carbon to the atmosphere as CO_2.

Processes = Transformation, **Principles** = Tracing Matter, **Scale** = Ecosystem

Interpreting Student Responses: This question asks students to realize that carbon is removed in crop material. Therefore, when crops are no longer grown, more dead plant material is present to enter the soil organic matter pool. In addition, cultivation of annual crop plants enhances the decomposition of soil organic matter. Discontinuation of cultivation will result in more perennial plants and less soil disturbance. Most students recognize that harvested crop biomass contains a large amount of carbon that is not entering the soil at the end of the year, but rarely recognize that cultivation practices result in the depletion of soil organic carbon.

7. Each Spring, farmers plant about 5-10 kg of seed corn per acre for commercial corn production. By the fall, this same acre of corn will yield approximately 4-5 metric tons (4,000 – 5,000 kg) of dry, harvested corn. What percent of the mass of the harvested corn was once in the following substances and locations? Fill in the blanks with the appropriate percentages; you may use 0% in your response if you

feel it is appropriate.

2.5 % from absorption of mineral substances from the soil via the roots
<1 % from absorption of organic substances from the soil via the roots
95 % from incorporation of CO_2 gas from the atmosphere into molecules by green leaves
2.5 % from incorporation of H_2O from the soil into molecules by green leaves
0 % from absorption of solar radiation into the leaf

Processes = Photosynthesis **Principles** = Tracing Matter and Energy, **Scale** = Ecosystem

Interpreting Student Responses: Many students can recite and/or write the chemical equation for photosynthesis, but do not properly apply it to questions about mass gain in plants. Most often, students think that mass is gained by absorbing materials through their roots – including carbon based substances. For a student to reason correctly about the consequences of biofuel production, they must understand the origin of the carbon in the biofuels.

Gasoline Diagnostic Question Cluster

Millions of years ago, the carbon atoms in gasoline were originally in carbon dioxide molecules in the atmosphere. Carbon dioxide was converted to organic forms during photosynthesis by plants. When the plants died, they were not decomposed, but instead were compressed in the Earth's crust for millions of years, ultimately resulting in the crude oil formation. The oil is refined into gasoline, and burned in internal combustion engines, which provides the energy necessary for movement. However, the carbon atoms once contained deep in the Earth's crust are released to the atmosphere during combustion, which has resulted in sharp increases in global atmospheric carbon dioxide levels. In this DQC, students are asked to trace carbon through the formation of gasoline, combustion and into the atmosphere. Questions one and two ask students to trace carbon through the entire history of gasoline, and subsequent questions are designed to further diagnose student difficulties in understanding the many processes involved in gasoline. Understanding the processes that govern matter transformations allows students to explain the consequences of burning gasoline as a transportation fuel.

Gasoline Diagnostic Question Cluster

Please answer the questions below as carefully and completely as you can.

1. The carbon atoms in gasoline were originally carbon dioxide (CO_2) in the atmosphere. Using words and or drawings, trace the carbon atoms from CO_2 in the atmosphere to octane (C_8H_{18}) in gasoline. Include as many steps and as much detail as you can.

Millions of years ago, a plant converted carbon dioxide to glucose during photosynthesis. The glucose was transported within the plant and used to synthesize part of the plants biomass during biosynthesis processes. When the plant died, environmental factors prevented decomposers from accessing the dead plant material; therefore it was not decomposed. The plant material was compressed within the earth for many years, in which the plant material was converted to crude oil now found in the Earth. The oil was extracted by humans, and the molecules in the crude oil were converted to octane, which contained the original carbon dioxide that was in the atmosphere.

Processes = Multiple Processes, **Principles** = Tracing Matter and Energy, **Scale** = Ecosystem, Atomic-Molecular

Interpreting Student Responses: Students must trace carbon through many steps in this question, including photosynthesis, transformation within a plant, and after the plant dies. They must understand that decomposition cannot occur, which would result in the carbon atoms being transferred to the atmosphere as carbon dioxide. Finally, students must trace the carbon atoms during the process of refining crude oil into gasoline. All of these steps, combined with Question number two, are important to consider when tracing carbon atoms when considering gasoline.

2. Gasoline is mostly a mixture of hydrocarbons such as octane: C_8H_{18}. Decide whether each of the following statements is true (T) or false (F) about what happens to the atoms in a molecule of octane when it burns.

T F Some of the atoms in the octane are incorporated into carbon dioxide in the air.
T **F** Some of the atoms in the octane are incorporated into air pollutants such as ozone or nitric oxide.
T **F** Some of the atoms in the octane are converted into energy that moves the car.
T **F** Some of the atoms in the octane are burned up and disappear.
T **F** Some of the atoms in the octane are converted into heat.
T F Some of the atoms in the octane are incorporated into water vapor in the atmosphere.

Processes = Combustion, **Principles** = Tracing Matter and Energy, **Scale** = Atomic-Molecular

Interpreting Student Responses: This question about gasoline combustion is a good complement to question 1 above, which asks about the origin of gasoline. You can consider these questions together as the multiple process question. Gasoline is combusted to release heat energy which is converted to mechanical energy. However, students don't always trace matter during this process, often incorrectly converting matter to energy. In addition, many students believe that gasoline combustion results in higher emissions than biofuel combustion. Therefore, they don't trace matter effectively, often because they convert matter to energy. We ask the same question about ethanol from biofuels in the Biofuels DQC. Incorrect student responses are found for all six true/false questions. Most commonly, students incorrectly convert matter to energy.

3a. On average, how long do you think a molecule of carbon dioxide remains in the atmosphere after being released by a human being?

Anywhere between 2 and 20 years would be considered appropriate answers. Five – ten years is considered to be the average residence time for CO_2 in the atmosphere.

Processes = Carbon Residency Time, **Principles** = Tracing Matter, **Scale** = Atomic-Molecular

Interpreting Student Responses: The major reason for asking this question is to lead into question 3b. However, students don't tend to recognize how long a molecule of carbon dioxide remains in the atmosphere before being transformed to organic carbon through photosynthesis or dissolving into a water body. In multiple choice format, students tend to choose either a 5 year, 50 year, or 350 million year residence time. Students providing very long time frames don't appear to understand the path that carbon takes between the biosphere and atmosphere.

3b. After a period of time, the carbon atom released by a human being will leave the atmosphere. Where does the carbon atom go when it leaves the atmosphere?

Carbon in the atmosphere is in the form of carbon dioxide. It leaves the atmosphere when a plant utilizes the molecule of carbon dioxide in photosynthesis. During this process, carbon dioxide is combined with water to form glucose, an organic carbon molecule.

Processes = Photosynthesis, **Principles** = Tracing Matter, **Scale** = Ecosystem, Atomic-Molecular

Interpreting Student Responses: This question specifically asks students to recognize the process of photosynthesis without being explicitly asked about photosynthesis. Students may respond with answers that say carbon escapes the atmosphere, which incorrectly conserves matter. They may also say it is incorporated into animals during breathing, or dissolved into the Earth. They may also respond with an alternative correct answer that carbon dioxide dissolves into water bodies, and is converted to carbonate molecules, but this is unlikely unless they have learned this process.

4a. When you are riding in a car, the car burns gasoline to make it run. Eventually the gasoline tank becomes empty. What happened to the **matter** the gasoline was made of?

The matter in the gasoline was converted to water vapor and carbon dioxide, both of which move to the atmosphere.

4b. When the gasoline tank became empty and the car stopped, where did the **energy** of gasoline go?

The energy contained as chemical bond energy in the gasoline was transferred to mechanical energy that moved the automobile, and much of the energy was lost as heat.

4c. What was the ultimate source of energy for the gasoline?

Sunlight, which was captured by plants millions of years ago, and stored as chemical bond energy as the plant material was compressed (not decomposed) over time.

4d. Do cars need air in order to run? **Yes** / No
Please explain your answer.

Air contains oxygen, which is a reactant during the process of gasoline combustion. Oxygen gas reacts with the gasoline to produce carbon dioxide and water.

Processes = Combustion, Photosynthesis, **Principles** = Tracing Matter and Energy, **Scale** = Ecosystem Explicit

Interpreting Student Responses: A series of questions ask students to trace matter and energy during the process of combustion. Questions 4a and 4b are good complements, that they require students to correctly separate matter and energy during combustion, and trace matter and energy after combustion. Tracing energy also requires knowledge of the source of energy – many students believe that energy is "created" during combustion – not correctly tracing energy from sunlight into gasoline and out as heat.

5. When a match burns the energy released
   - **A) comes mainly from the match.**
   - B) comes mainly from the air.
   - C) is created by the fire.
   - D) comes from the energy that you used to strike the match.
   - E) none of the above

Please explain your answer.

When a match burns, the energy released is in the form of heat. This energy was previously in the form of chemical bond energy within the match, and was released when the bonds were broken during combustion. The ultimate origin of energy is sunlight, which is captured by plants and stored in the bonds within the plant.

Processes = Combustion, **Principles** = Tracing Energy, **Scale** = Organismal Explicit

Interpreting Student Responses: All responses – A, B, C and D – are common answers provided by students, with A being the least common response. Students know that air (oxygen) is needed for combustion, and often assume that the oxygen is also the energy source (Answer B). Answer C indicates unprincipled reasoning – that energy can be created spontaneously, and does not ultimately come from the sun. Striking the match is important for initiation of this energy transfer, but is not the energy source during the combustion of the match.

6. The atmosphere's ability to keep the surface of the earth warm is caused by the ...
   - A) seasons.
   - **B) greenhouse effect.**
   - C) ozone layer.
   - D) wind.
   - E) Responses B. and C. are correct.

Processes = Greenhouse Effect, **Principles** = Tracing Matter and Energy, **Scale** = Ecosystem Explicit

Interpreting Student Responses: Students must understand the process by which climate change is occurring, as gasoline combustion results in carbon dioxide released to the atmosphere, which is a greenhouse gas and traps heat near the Earth's surface. This question does not fit directly under the general principles of tracing matter or energy, but is essential to understanding of climate change due to fossil fuel combustion. Students may understand carbon cycling, but may fail to correctly answer multiple process questions due to limited knowledge of the greenhouse effect. Many students attribute climate change to the depletion of the ozone layer. Very few students choose D as the correct answer.

7a. Scientists have discovered several microorganisms that are able to decompose gasoline. What happens to the carbon atoms in the gasoline during decomposition?

Decomposers convert the gasoline molecules to smaller gaseous molecules such as carbon dioxide and methane.

Processes = Respiration, **Principles** = Tracing Matter, **Scale** = Atomic-Molecular

Interpreting Student Responses: We ask this question to understand student ability to trace matter during decomposition, and that carbon atoms in gasoline are converted to either carbon dioxide or methane, which are gaseous forms of carbon. The form of carbon released to the atmosphere is irrelevant – it is more important that students trace the carbon to the atmosphere. Specifically, we want to know whether students consider decomposition of gasoline to be a different process than decomposition of organic plant material in soil, which is asked about in Question 6b of the Biofuels DQC. It is likely that many students will only provide answers that leave carbon in the soil, not emitting the carbon to the atmosphere.

7b. Do the carbon atoms following decomposition by microorganisms end up in a different location than if the gasoline was burned in a car? Circle Yes or **No**.
Please explain your answer.

Cellular respiration is the process by which decomposers break down solid carbon containing molecules. The products of cellular respiration are carbon dioxide and water, which are the same products of the combustion process if gasoline was burned in a car.

Processes = Respiration, Combustion, **Principles** = Tracing Matter, **Scale** = Atomic-Molecular

Interpreting Student Responses: Both cellular respiration and combustion are processes that oxidize solid or liquid forms of carbon, but many students don't consider these two processes to be similar. A student providing a correct answer would need to apply principled reasoning about tracing matter. Students that answer with "Yes" or incorrectly explain why they answered with "No" do not understand the processes of cellular respiration and combustion.

Appendix I. Questions Organized by Process

List of All Multiple Process Questions:

Question Name	DQC	Question Number
ATMBALANCE	Carbon Balance	1
BIOFUEL	Biofuels	1
CARBNATOR	Carbon in Nature	1
CARBPOOL	Forest Carbon	1
ENERPYR1	Energy Pyramid	1
GASTRACE	Gasoline	1
GRANJOHN	Grandma Johnson	1
KLGSEASON	Keeling Curve	1
TROPFOREST	Rainforest	1
TROPMASS	Trophic Transfer	1

List of All Photosynthesis Questions:

Question Name	DQC	Question Number
CARBRESB	Biofuels Gasoline	3b 3b
CORNGROW	Energy Pyramid Keeling Curve Biofuels	7 3 7
ECOENER1	Rainforest	2a
ENERGYL1	Rainforest	3
FOODMOVE	Carbon in Nature Trophic Transfer Carbon Balance	2 2 3
LDTREES	Energy Pyramid	3
MAPLEMASS	Grandma Johnson	3
PLANTRESP1	Forest Carbon	3
PLANTRESP2	Forest Carbon	2
PLANTRESPA	Trophic Transfer	3
TREEFOREST	Rainforest	6
WOLVSUN	Rainforest	2b
GRASSCO2B	Carbon in Nature	5
GASENMATTC	Gasoline	4c
MASSCHANGEA	Forest Carbon	6a

List of All Transformation Questions:

Plant to Plant

Question Name	DQC	Question Number
TREEFOREST	Rainforest	6
CARBPATHSB	Forest Carbon Grandma Johnson Trophic Transfer	5b 4b 7b
FOODMOVE	Carbon in Nature Trophic Transfer	2 2
LDTREES	Energy Pyramid	3

Plant to Animal

Question Name	DQC	Question Number
CARBPATHSC	Forest Carbon	5c
	Grandma Johnson	4c
	Trophic Transfer	7c
ENERGAINA	Rainforest	4a
FWFEEDING	Carbon in Nature	4
	Trophic Transfer	6
GRAPGLUC	Energy Pyramid	4
WOLVSUN	Rainforest	2b

Plant to Soil

Question Name	DQC	Question Number
CARBPATHSD	Forest Carbon	5d
	Grandma Johnson	4d
	Trophic Transfer	7d
SOILCLOSS1	Biofuels	6a
SOILCLOSS4	Biofuels	6d
FALLEAVEA	Carbon Balance	5a
	Keeling Curve	4a
ORIGFUEL	Carbon Balance	4
SOILCLOSS3	Biofuels	6c
GASENMATTC	Gasoline	4c

Plant to Decomposer

Question Name	DQC	Question Number
BREADMOLD	Energy Pyramid	6
	Rainforest	5
	Grandma Johnson	2

Animal to Animal

Question Name	DQC	Question Number
COYOTE	Grandma Johnson	5
DEERWOLV	Trophic Transfer	5
FWFEEDING	Carbon in Nature	4
	Trophic Transfer	6

Energy Loss

Question Name	DQC	Question Number
ENERGAINB	Rainforest	4b
ENERPYR3	Energy Pyramid	2
TROPHENER	Energy Pyramid	5

List of All Respiration Questions

Plant

Question Name	DQC	Question Number
CARBPATHSA	Forest Carbon	5a
	Grandma Johnson	4a
	Trophic Transfer	7a
PLANTRESPA	Trophic Transfer	3
CO2ATM	Carbon in Nature	6
PLANTRESP2	Forest Carbon	2
PLANTRESP1	Forest Carbon	3

Animal (non decomposer)

Question Name	DQC	Question Number
FAT15	Trophic Transfer	4
CO2ATM	Carbon in Nature	6
PLANTRESP1	Forest Carbon	3
MASSCHANGEB	Forest Carbon	6b

Decomposer

Question Name	DQC	Question Number
BREADMOLD	Grandma Johnson	2
	Energy Pyramid	6
	Rainforest	5
COMPOST	Rainforest	7
DECDIED	Carbon in Nature	3
MASSCHANGEC	Forest Carbon	6c
LDTREES	Energy Pyramid	3
GASDECOMPA	Gasoline	7a
POTATOMASS	Grandma Johnson	6
SOILCLOSS2	Biofuels	6b
SOILCLOSS3	Biofuels	6c
SOILRESP	Forest Carbon	4
FALEAVEA	Carbon Balance	5a
	Keeling Curve	4a
FALEAVEB	Carbon Balance	5b
	Keeling Curve	4b

List of All Combustion Questions

Question Name	DQC	Question Number
BIOCOMBUST	Biofuels	5
COALELEC	Carbon Balance	6
ENERMTCH	Gasoline	5
OCTANE	Gasoline	2
QANGASCO	Keeling Curve	5
CO2ATM	Carbon in Nature	6
GASDECOMPB	Gasoline	7b
GASENMATTB	Gasoline	4b
GASENMATTD	Gasoline	4d
GASENMATTA	Gasoline	4a

List of All carbon Residence Time Questions (could this be transformation instead?)

Question Name	DQC	Question Number
CARBRESA	Biofuels	3a
	Gasoline	3a

List of All Atmospheric/Greenhouse Gas Questions

Question Name	DQC	Question Number
GLOBWAMC	Carbon Balance	2
	Biofuels	2
EARTHWARM	Keeling Curve	6
	Gasoline	6

List of All Biogeograpy Questions

Question Name	DQC	Question Number
GLOBELAND	Keeling Curve	2

List of All Biofuel Production Questions

Question Name	DQC	Question Number
BIOFUEL2	Biofuels	4

Appendix II. Questions organized by process within DQC's, and within Topics.

Carbon Cycling DQC's

Processes	**Forest Carbon**	**Grandma Johnson**
Multiple Process	CARBPOOL (1)	GRANJOHN (1)
Photosynthesis	PLANTRESP2 (2), PLANTRESP1 (3), MASSCHANGE (6a)	MAPLEMASS (3)
Transformation – Plant to Plant	CARBPATHSB (5b)	CARBPATHSB (4b)
Transformation – Plant to Soil	CARBPATHSD (5d)	CARBPATHSD (4d)
Transformation – Plant to Animal	CARBPATHSC (5c)	CARBPATHSC (4c)
Transformation – Plant to Decomposer		BREADMOLD (2)
Transformation – Animal to Animal		COYOTE (5)
Respiration – Decomposition	SOILRESP (4), MASSCHANGEC (6c)	BREADMOLD (2), POTATOMASS (6)
Respiration – Plants	CARBPATHSA (5a), PLANTRESP2 (2), PLANTRESP1 (3)	CARBPATHSA (4a)
Respiration – Animals	PLANTRESP1 (3), MASSCHANGEB (6b)	

Trophic Levels DQC's

Processes	**Carbon in Nature**	**Trophic Transfer**
Multiple Process	CARBNATOR (1)	TROPMASS (1)
Photosynthesis	FOODMOVE (2), GRASSCO2B (5)	PLANTRESPA (3), FOODMOVE (2)
Transformation – Plant to Plant	FOODMOVE (2)	FOODMOVE (2), CARBPATHSB (7b)
Transformation – Plant to Soil		CARBPATHSD (7d)
Transformation – Plant to Animal	FWFEEDING (4)	FWFEEDING (6), CARBPATHSC (7c)
Transformation – Animal to Animal	FWFEEDING (4)	DEERWOLV (5), FWFEEDING (6)
Respiration – Decomposition	DECDIED (3)	
Respiration – Plants	CO2ATM (6)	PLANTRESPA (3), CARBPATHSA (7a)
Respiration – Animals	CO2ATM (6)	FAT15 (4)
Combustion	CO2ATM (6)	

Energy Flow DQC's

Processes	**Energy Pyramid**	**Rainforest**
Multiple Process	ENERPYR1 (1)	TROPFOREST (1)
Photosynthesis	LDTREES(3), CORNGROW (7),	ECOENER1 (2a), WOLVSUN (2b) ENERGYL1 (3), TREEFOREST (6)
Transformation – Plant – Plant	LDTREES (3)	TREEFOREST (6)
Transformation Plant – Animal	GRAPGLUC (4)	ENERGAINA (4a)

		WOLVSUN (2b)
Transformation – Plant to Decomposer	BREADMOLD (6)	BREADMOLD (5)
Transformation – Energy Loss	ENERPYR3 (2), TROPHERNER (5)	ENERGAINB (4b)
Respiration – Decomposition	BREADMOLD (6), LDTREES (3)	COMPOST (7), BREADMOLD (5)

Understanding Climate Change DQC's

Processes	Carbon Balance	Keeling Curve
Multiple Process	ATMBALANCE (1)	KLGSEASON (1)
Photosynthesis	FOODMOVE (3)	CORNGROW (3)
Transformation – Plant to Soil	ORIGFUEL (4), FALEAVEA (5a)	FALEAVEA (4a)
Respiration – Decomposition	FALEAVEA (5a), FALEAVEB (5a)	FALEAVEA (4a), FALEAVEB (4b)
Combustion	COALELEC (6)	QANGASCO (5)
Atmosphere – Greenhouse effect	GLOBWAMC (2)	EARTHWARM (6)
Biogeography		GLOBELAND (2)

Carbon Dynamics in Energy Production DQC's

Processes	Biofuels	Gasoline
Multiple Process	BIOFUEL (1)	GASTRACE (1)
Photosynthesis	CARBRESB (3b), CORNGROW (7)	CARBRESB (3b), GASENMATTC (4c)
Transformation – Plant to Soil	SOILCLOSS1 (6a), SOILCLOSS3 (6c), SOILCLOSS4 (6d)	GASENMATTC (4c)
Respiration – Decomposition	SOILCLOSS2 (6b), SOILCLOSS3 (6c)	GASDECOMPA (7a)
Combustion	BIOCOMBUST (5)	OCTANE (2), ENERMTCH (5), GASDECOMPB (7b), GASENMATTA (4a), GASENMATTB (4b), GASENMATTD (4d)
Greenhouse Effect	GLOBWAMC (2)	EARTHWARM (6),
Carbon Residency Time	CARBRESA (3a)	CARBRESA (3a)
Biofuel Production	BIOFUEL2 (4)	

Appendix III. Overlapping Questions in BIO-DQC's.

Solid lines with numbers indicate that two questions are the same between two DQC's.