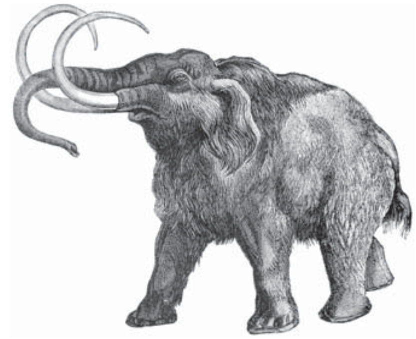
Dust to Dust: The Carbon Cycle



by
Jennifer Y. Anderson, Health Science, Nursing, Brookdale Community College
Diane R. Wang, Biology, Plant Breeding and Genetics, Cornell University
Ling Chen, Science Department, Borough of Manhattan Community College

Tom was visiting his grandfather, a retired high school chemistry teacher, who lived in a nearby adult community apartment. Tom, a freshman in college, wanted to talk to his grandfather about something he had seen on TV.

"Grandpa, have you been watching the National Geographic channel lately? I saw a program on it called *Waking the Baby Mammoth*," Tom said excitedly. "It's a documentary about the discovery of a baby mammoth from 40,000 years ago!"

"Oh, yes," said Tom's grandfather. "I saw that program. The people who found her in Siberia named her Lyuba. She's the oldest and best preserved woolly mammoth discovered so far."

"I wonder how scientists determined Lyuba's age," said Tom.

"Well, they probably used carbon dating."

"What's that?" asked Tom.

"Radiocarbon dating, or carbon dating, is a technique used to determine time passed after a living organism died or the age of a specimen according to the radio activity of its remaining carbon, found in any organic matter that makes up the specimen—for example, bones, cloth, wood or plant fibers."

"How does it work?"

"Well, all living things are made up of carbon. Some of the carbon is unstable and breaks down over time after organisms die; you can measure the unstable (radioactive) carbon levels in fossils to determine how long ago the individuals died. Carbon is the basis of life on earth, you know, Tom. Where do you think carbon in our bodies comes from?"

"From food, of course," said Tom.

"Right on the money. There are two kinds of food sources: plant and animal. A plant combines CO_2 (captured from the air), water (from the ground), and solar energy (in the form of light with two wavelengths: 680 nm and 700 nm) to produce carbohydrates and oxygen. This process is called photosynthesis, and it is essential to all life on earth."

Tom's grandfather continued: "Through photosynthesis, plants produce carbohydrates and oxygen; both are vital to sustain life for all animals, including humans. The carbohydrates provide carbon and energy; oxygen is essential in releasing the energy stored in the carbohydrates in the metabolic process."

Tom's grandfather paused, then asked him a question, like they were in class: "Tom, did you know that a very small amount of CO_2 in nature contains the unstable kind of carbon atom and therefore is radioactive?"

"Really?" said Tom. "Does it have something to do with the carbon dating technique?"

"Yes. There are three kinds of carbon atoms: carbon-12, carbon-13, and carbon-14. Although C-12 and C-13 are non-radioactive and stable, C-14 is the opposite; it's radioactive and unstable. In chemistry, we call C-12, C-13, and C-14 isotopes since they are all carbon; they just have different numbers of neutrons in their nuclei. CO_2 containing all of these isotopes is obtained by plants during photosynthesis. When animals eat plants, they in turn assimilate C-12, C-13, and C-14, and then that carbon is passed up the chain to any animals who eat these animals, and so on. Radioactive C-14 is found in all living things, including you and me."

"Oh, I get it. According to the amount of remaining carbon, archaeologists can determine the age of a fossil," said Tom.

"C-14 to be exact."

"But I thought C-12, C-13, and C-14 were all carbon." Tom was a little confused.

"It's true that they all have six electrons and the same chemical properties," explained Tom's grandfather. "But they are different at the subatomic level, the nucleus, to be precise. Atoms, the smallest particles of a substance, can be further divided into three subatomic particles: protons, neutrons, and electrons. Protons and neutrons are found inside the nucleus, a very dense region within an atom, while the electrons are outside the nucleus region."

"So, that means six electrons can be found outside the nucleus regions in all three carbon isotopes. But how are C-12, C-13, and C-14 different in the nucleus?" asked Tom.

"They have different numbers of neutrons even though each has six protons in the nucleus. C-14 has eight neutrons, giving it a total of 14 particles (six protons plus eight neutrons) within the nucleus, making C-14 unstable, or radioactive. Over time, the nucleus of C-14 breaks down via spontaneous decay, and releases particles and energy to be in a more stable form. Radiation, the released energy, can be measured during the decay process. On the other hand, C-12 has only six neutrons, a total of 12 particles (six protons plus six neutrons) inside the nucleus, which make C-12 atoms stable, so its nucleus does not break down. As a result, there is no energy released. Same goes for C-13, which contains a total of 13 particles in the nucleus (6 protons plus 7 neutrons)."

"I see," said Tom. "So, after the decay, is C-14 still carbon?"

"Nope," said his grandfather. "One of the neutrons in C-14 splits into a proton and electron. The proton remains in the nucleus, but the electron is released from the nucleus with high energy or radiation. The addition of a proton makes the resultant atom a non-radioactive N-14."

"High energy electrons released from the nucleus? That's interesting," said Tom. "Do these high energy electrons have a special name to distinguish them from those found outside the nucleus region?"

"Good question. The high energy electrons emitted from the nucleus are called beta (β) particles or β radiation. Measuring and comparing the intensity of β-radiation is the basis of the carbon dating technique. The higher the radiation, the more C-14 remains."

"So, can I say that the older an object is, the less C-14 remains; and therefore the weaker the radiation it emits?"said Tom.

"Mm-hmm." His grandfather nodded his head. "After an organism dies, it cannot obtain more C-14. Therefore, the level of C-14 in its body begins to decline. By comparing the amount of C-14 left in a fossil with that of a living organism, scientists can figure out how long that fossil has been around. In addition, the half-life concept is needed to pinpoint the age of the fossil. Lyuba is a perfect example to understand the carbon dating half-life, and thus the age of her remains."

"What's *half-life?"* asked Tom.

"The half-life is the time needed for half the total amount of a radioactive element to break down. The half-life of C-14 is known to be approximately 5,730 years. Let's round it up to 6,000 years for simplicity. A fossil of 6,000 years old, which is one half-life, will then have half of its C-14 left as compared to a living organism."

"So if a quarter of the C-14 remains in the fossil, then two half-lives have passed, and the fossil is about 12,000 years old," Tom said.

"Excellent, Tom! Can you tell me how many half-lives of C-14 in Lyuba's remains have gone through?"

"Let me see. Her remains are about 40,000 years old; one half-life of C-14 is approximately 6,000 years. It's almost seven half-lives."

"Well done! Tell me how did you calculate it so quickly?" Tom's grandfather asked.

"I divided 40,000 years (the age of her remains) by 6,000 years (the half-life of C-14); I then rounded the result to 7. Grandpa, I have another question for you: Where does radioactive carbon originally come?"

"The upper atmosphere. Since cosmic rays from outer space bombard the atmosphere constantly, when a neutron attacks nitrogen-14 (with 7 protons and 7 neutrons), one of the protons is knocked out and replaced by the neutron, and radioactive C-14 (which has 6 protons and 8 neutrons) is produced."

"Wow. So, in β-decay, C-14 becomes N-14, but in the bombardment, N-14 is transformed back to C-14. Carbon and nitrogen are next-door neighbors in the periodic table with only one proton and one electron difference. Now I see how they're related at the atomic level. Awesome!"

"Yep. This process is called nuclear chemistry in which new elements are produced. Did you know that another source of C-14 in the air is from the burning of fossil fuels?"

"What are fossil fuels?" asked Tom.

"They're fuels when dead plants and animals from millions of years ago decompose. An example of a fossil fuel is crude oil," explained his grandfather.

"Cool! Carbons transformed from ancient life to crude oil, to CO_2, and then incorporated into the food chain, back to life again.

"As the old saying goes: from dust to dust. It would be fair to say, Tom, that we are a collection of carbon. Life is a process of recycling chemicals, like carbon, oxygen, hydrogen, and nitrogen. All living organisms are chemically related to one another because we all share the same pool of elements."

"Does it mean that part of me might come from stars or dinosaurs?" asked Tom.

"Sure. We are part of the universe and a part of the universe is in us too. Life is chemistry and a precious gift; so eat well and live your life to the fullest."

"Will do, Grandpa."

Questions

1. What is photosynthesis?
2. Is photosynthesis an endothermic or exothermic reaction? Show the chemical equation.
3. Why is photosynthesis essential to the lives of animals on earth?
4. Compare isotopes of carbon, C-12, C-13, C-14; what do they have in common and how are they different?
5. In the upper atmosphere, high energetic neutrons in cosmic rays constantly collide with nitrogen-14 to produce carbon-14 (radioactive). Write the nucleus equation for this bombardment process, the origin of C-14.
6. What is half-life? (Use carbon as an example.)
7. Write the β decay nuclear equation of C-14. Explain the origin and the nature of the β particle.
8. What is the purpose of radiation in food industry? Is it safe to consume irradiated foods?
9. Why is CO_2 called one of the greenhouse gases?
10. Yttrium 90 (Y-90) is a beta emitter and a valuable clinical tool in internal radiation therapy for treating liver tumors. Y-90 has a short half life (less than three days). Implanted in a patient's tissue, it penetrates 2.5 mm, with a maximum range of 11 mm, which minimizes side effects to adjacent tissues. Write the Y-90 β-decay equation in which zirconium-90 is produced.
11. Diamond is also made of carbon. Can the carbon dating technique be used to determine the age of a diamond? Explain why or why not.