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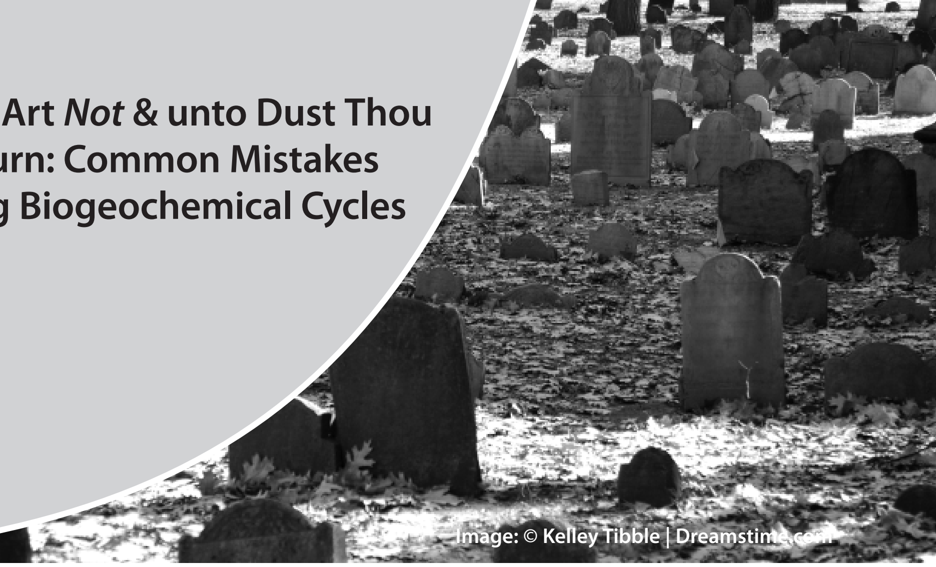
Dust Thou Art *Not* & unto Dust Thou *Shan't* Return: Common Mistakes in Teaching Biogeochemical Cycles

DAN O'CONNELL



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Abstract

When describing biogeochemical transfers, textbook authors have often overstated the role of soil while neglecting the role of carbon dioxide. Unfortunately, these errors align with naive biogeochemical intuitions. This article aims to increase awareness of the prevalence of such misconceptions and offers countermeasures. Avoiding these misconceptions becomes increasingly important as concerns over carbon emissions grow. In addition, because an accurate understanding of biogeochemical cycles can transform deeply held beliefs, successfully teaching this topic can have the collateral benefit of inspiring lasting interest in science.

Key Words: *Biogeochemical cycles; soil; climate change; misconceptions; carbon dioxide.*

Without ever opening their textbooks, my high school biology students can usually give a plausible-sounding account of biogeochemical cycles. First, they explain that plants take in nutrients from the soil. Then, animals come along, eat the plants, and build their bodies from the plant-derived materials. Finally, the animals and plants die, decompose, and give their bodies to the soil to restore the nutrients needed to sustain future generations. It is a simple, familiar, and beautiful tale – from soil, to plant, to animal and back. It is no wonder my students have learned it by heart.

Unfortunately, this familiar story is untrue. But, if you have difficulty spotting its errors, you are in good company. The authors of several of the most widely used and highly regarded biology and environmental science texts have the same trouble. These published errors are especially regrettable because they reinforce common misconceptions about biogeochemical transfers (Annenberg Foundation & Corporation for Public Broadcasting [CPB], 1997; Keeley et al., 2005; Koba & Tweed, 2009). This makes it particularly difficult for students to understand the truth (Treagust, 1988).

> *The idea that biomass comes from and returns to soil is too important and too pervasive a mistake to overlook.*

Often, the truth in science is stranger than fiction. Although I studied photosynthesis in middle school, high school, college, and graduate school, it was not until years later that its significance finally sank in. Plants do not eat *soil*. They eat *air*! More precisely, plants and all other autotrophs use carbon dioxide as their principal nutrient source. It accounts for about 90% of nutrient uptake. Water comes in a distant second, contributing only about 5% to plant dry mass. More than a dozen other nutrients combine to make up the remaining 5% (Markert, 1992; Freeman, 2008).[1]

Although it is widely understood that the biosphere is formed from just two main ingredients, CO_2 and H_2O, the fact is still astonishing. Carbon dioxide – an invisible, odorless, mildly toxic, and very rare atmospheric gas – is, by far, the biosphere's most important building material. Equally surprising, all but a tiny fraction of the material in dead organisms is quickly converted back to this same simple molecule (Falkowski et al., 2000). The small fraction of the biosphere's carbon that is sequestered as soil organic material is nutritionally unavailable to plants (Hungate et al., 1997; King, 1997). If decomposers did not vaporize almost all organic detritus, producers would soon be without a carbon source and life on earth would be devastated.

These facts are so important that they should be integral to any introductory course in biology or environmental science. Yet many authors not only fail to correct misconceptions about material cycles, they perpetuate them.

Such mistakes hinder a proper understanding of climate change, including its causes and possible solutions. This is one of the most pressing environmental issues of our time. So, it is imperative that these misconceptions be replaced with clear understandings. It is now evident that Earth's climate system is profoundly influenced by the amount of carbon dioxide in the atmosphere (Sarmiento & Wofsy, 1999). It is also clear that humans have been altering this amount at an alarming rate (Pachauri & Reisinger, 2007). Every student of biology and environmental science should appreciate that when producers perform photosynthesis, they build their bodies almost entirely from a greenhouse gas. Only by understanding this process can students hope to follow arguments for alternative fuels, reforestation, habitat preservation, and other strategies for mitigating anthropogenic CO_2.[2]

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[1] Unfortunately, in plant nutrition, the term "macronutrient" is used for nitrogen, potassium, calcium, phosphorus, magnesium, and sulfur – elements that constitute only a very small fraction of plant dry mass. A more accurate term would be "micronutrient." But this term is used to describe the set of even rarer elements whose total combined mass typically constitutes less than 1% of dry mass.

[2] This mistake also obscures the true importance of humus, which can improve fertility, but only indirectly, such as by changing the chemical and physical properties of soil.

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Correcting mistaken ideas about material cycles is also vital because this subject is so counterintuitive and interesting. Where do the materials in our body come from? Where do they eventually go? Where does fat go when a person loses weight? What do plants use to build their bodies? How are we dependent on atmospheric gases for our survival? The answers to these questions are so surprising as to offer golden opportunities for inspiring lasting interest in science. Teachers squander such opportunities when familiar but mistaken ideas about material cycles replace the unfamiliar and fascinating truth.

However, before addressing the widespread use of inaccurate and misleading accounts of material transfers, I ask you to briefly consider some of the possible sources.

○ The Sources of Misconceptions about Biogeochemical Cycles

Ask your class to complete this familiar phrase: "Ashes to ashes, dust to --." The text for this prayer, part of the English Burial Service, is derived from the Biblical verses in Genesis that tell of God's response after Adam and Eve have eaten the fruit from the forbidden tree.

> [17]Cursed is the ground for thy sake; in sorrow
> shalt thou eat of it all the days of thy life;
>
> [18]Thorns also and thistles shall it bring forth to
> thee; and thou shalt eat the herb of the field;
>
> [19]In the sweat of thy face shalt thou eat
> bread, till thou return unto the ground; for
> out of it wast thou taken: for dust thou art,
> and unto dust shalt thou return.
>
> Genesis 3:17–19, King James Version

Although the author of Genesis was surely not striving to describe biogeochemical cycles literally or with scientific accuracy, this description holds great intuitive appeal. For those trying to understand the source and fate of biological material, the Genesis story gives a common-sense answer. Throughout these verses, the materials of the biosphere are shown to come from the ground. Not only are thorns and thistles produced by the ground, but Adam and Eve are cursed to eat of the ground, which their bodies are said to be made of, and fated to return to.

In 350 BCE, about a century after Genesis was written, Aristotle addressed a similar question: Where do the materials that make up plants come from? Unfortunately, he reached a similar conclusion. Aristotle began by noting that the body is divided into an upper, a middle, and a lower part. Food enters animals in the upper part, whereas excretion is performed by the lower part. Plants, he reasoned, are the reverse of animals in this respect. So Aristotle mistakenly claimed that "there is a correspondence between the roots in a plant and what is called the mouth in animals, by means of which they take in their food" (translated by G. R. T. Ross; http://classics.mit.edu/Aristotle/youth_old.1.1.html). Unfortunately, Aristotle's mistake was viewed as scientific truth for hundreds of years (King, 1997).

Still, it is easy to imagine how the mistake could have arisen. When compared to carbon dioxide, soil appears to be much more potent and substantial. Playing soil through one's fingers, the harvest bounty can seem latent within. Soil is where seeds are planted. Soil is what farmers till, fertilize, and water. Gardeners everywhere are advised to treat soil with the utmost care. Indeed, the status of soil has sometimes been elevated to that of a living thing (Harris, 2005), which it certainly is not. But to the uneducated, soil can appear to be both the source and final resting place of organic material. We have all casually observed plants growing where soil is present and not growing where soil is absent. Experiences like these reinforce the mistaken belief that soil stores the primary nutrients for plants. This makes material cycles a particularly hard subject for students to grasp (Barker, 2001; Koba & Tweed, 2009).

○ A Critique of Materials Used for the Teaching of Biogeochemical Cycles

Although the essential details of material cycles, such as the carbon cycle, have been established for over 50 years, it is not uncommon to encounter passages like the following:

> Producers that supply food for us and other consumers get the nutrients they need from soil and water. Indeed you are mostly composed of soil nutrients imported into your body by the food you eat. (Miller & Brewer, 2008)

Both of the sentences above are almost completely incorrect. Producers get only a tiny fraction of the nutrients they need from soil, and we are composed almost entirely from atmospheric carbon dioxide and water. Yet this quotation is taken from a textbook in its 15th edition!

Sadly, Tyler Miller and Richard Brewer's (2008) *Living in the Environment* is far from alone in misrepresenting biogeochemical cycles. The North Carolina Department of Agriculture and Consumer Services misinforms us that plants grow by "absorbing nutrients from the soil" (see http://www.ncagr.gov/cyber/kidswrld/plant/nutrient.htm). Likewise, Johnson and Raven (2006) summarize biogeochemical cycles this way:

> Carbon atoms, for example, are passed from one organism to another in a great circle of use. Producers are eaten by herbivores, herbivores are eaten by predators, and top predators die and decay; their carbon atoms then become part of the soil to feed the producers in a long and complex cycle that reuses this important element.

I wish there were a more delicate way to respond to this description, but it is just plain wrong. It entirely omits the importance of atmospheric gases stating instead that producers obtain carbon from the soil. A subsequent chapter on terrestrial adaptations of plants repeats this error (Johnson & Raven, 2006).

Surprisingly, when Scott Freeman's otherwise outstanding textbook tackles biogeochemical cycles it makes a similar error. Indeed, Freeman's scheme for material cycles (Freeman, 2008: figure 54.13) could have been drawn by Aristotle himself. The figure depicts a tree absorbing nutrients from the soil using only its roots and not its leaves. The leaves are shown being eaten by a deer, which assimilates the plant nutrients. Finally, the materials from both the tree and the deer are shown returning to the soil, not to the atmosphere. The role of CO_2 is not mentioned in the figure, its caption, or the accompanying text.

While it is inevitable that some details will be left out of any generalized scheme, the most essential details should be the last to go. A summary of biogeochemical cycles that includes soil but not atmospheric gases is like a description of blood that mentions only white cells and not red.[3]

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[3] The idea that plants get almost all nutrients from the soil is comparable to the notion that New York City is 130 miles from San Francisco. Both estimates are off about twenty-fold.

Biology, by Ken Miller and Joseph Levine, is perhaps the most widely used high school biology textbook in the United States. Fortunately, it does a much better job of describing the importance of CO_2. Still, the authors' list of essential plant nutrients does not include carbon, hydrogen, or oxygen. Instead, their list and the accompanying text describe nitrogen, phosphorus, potassium, magnesium, and calcium as the "most important" plant nutrients (Miller & Levine, 2006). In fact, none of these comes anywhere close to carbon, oxygen, or hydrogen in supplying biomass.[4]

When authors deal explicitly with biosphere–atmosphere transfers, one might expect such mistakes to disappear. Descriptions of material flowing between biosphere and atmosphere should be potent reminders of the importance of the atmosphere as the main reservoir of nitrogen and of biologically available carbon. However, after Sylvia Mader explains the role of CO_2 as the carbon source for producers and consumers, the next sentence states, "When organisms (e.g., plants, animals, and decomposers) respire, a portion of this carbon is returned to the atmosphere as carbon dioxide" (Mader, 2004). The rest is said to contribute to carbon deposits, such as soil carbon, ocean sediments, and fossil fuel deposits. Given the Aristotelian tendencies of students to think of soil as a primary reservoir of plant nutrients, it seems prudent to compare Mader's "portion" that returns with the rest. What fraction of the organic material produced each year contributes to the formation of soil, fossil fuels, and other forms of sequestered carbon? Mader makes it sound like the majority of assimilated carbon is headed for sequestration. Could "a portion" be more than 50 percent? Fortunately, Mader's accompanying figure caption provides the answer. About 120 gigatons of carbon are removed each year from the atmosphere by photosynthesis. About 60 gigatons return to the atmosphere through animal and plant respiration, and 60 more return to the atmosphere through decay, which is really just another name for respiration performed by decomposers. So, this caption (but not the main text) indicates that essentially all of the carbon that is converted to organic material each year is converted back to carbon dioxide. In other words, the "portion" of assimilated carbon returned to the atmosphere is approximately 100% (Mader, 2004).

○ How to Address Misconceptions about Material Cycles

Any manuscript as ambitious as a biology textbook is bound to contain errors. Only a mean-spirited nitpicker would draw public attention to unimportant or isolated textbook errors. But the idea that biomass comes from and returns to soil is too important and too pervasive a mistake to overlook. One obvious corrective step is to substitute accurate, clear resources in place of flawed texts. This is easily done. For example, *Biology* by Neil Campbell does a fine job of consistently avoiding the inaccuracies described above (Campbell et al., 1999).

Another excellent source is *Biology: Exploring the Way Life Works* (Hoagland et al., 2001). The authors not only avoid inaccuracies; they write with unusual clarity, emphasizing key facts judiciously. When addressing the sources of biological matter and energy, they offer the bold section title "Life runs on sugar."

Although nearly all my students have previously been asked to memorize the chemical equation for photosynthesis, they have not internalized its importance in the carbon cycle. One reason may be that photosynthesis is typically presented in lessons about energy, and not in those about nutrition or ecology. Of course, photosynthetic products are not only used for energy. If they were, photosynthetic organisms would not be able to build their bodies; nor would their dependent consumers be able to build theirs. Life requires the *anabolic* utilization of the products of carbon fixation. These products are the building blocks for the biosynthesis of amino acids, lipids, nucleic acids, and almost all other essential biological molecules.

By contrast, my students typically think of "sugar" as an unhealthy additive found in candy bars or soft drinks. They do not see it as an indispensable anabolic feedstock for the biosphere. *Biology: Exploring the Way Life Works* combats this misconception nicely when the text points out that photosynthetic organisms make enough sugar each year to fill a 30-million-mile-long freight train. This supply of sugar, Hoagland et al. tell us, sets the budget for nearly all the energy use and biosynthesis that can occur in the biosphere – which brings the biogeochemical importance of photosynthesis into clear focus.

Unfortunately, prior beliefs are notoriously difficult to change. Merely assigning even the best textbook readings seems unlikely to reform students' beliefs about material cycles. I recommend instead that teachers begin by uncovering these beliefs. Ask students "Where does the material in your body come from?" When they cite food and drink, push them to explain how the material got into their food or drink.[55] Explain that this question really amounts to asking how producers acquire nutrients. Research shows that even accomplished high school and college students answer this question like Aristotle, pointing mistakenly again and again to soil (Annenberg Foundation & CPB, 1997). Likewise, when asked to explain where the organic material of terrestrial organisms will end up, students describe a cycle, with organic material somehow returning to the soil (Annenberg Foundation & CPB, 1997).

One strategy for addressing these mistakes is to simply remind students that for almost 90% of the time that life has existed on Earth, it thrived without soil (Campbell et al., 1999). Until 450 million years ago, almost all life was restricted entirely to aquatic and marine environments. Plants with the ability to take up material from soil arose long after animals. Although soil composition ranks among the most powerful abiotic influences on contemporary terrestrial ecosystems, such ecosystems are historical oddities. Nevertheless, as odd as they are, their main source of materials is the same as that used throughout the first 3 billion years of life on earth: atmospheric CO_2.

Describing epiphytes and explaining hydroponic agriculture are two more ways to show that producers, even plants, can flourish without soil.

Another way to avoid Aristotle's mistake is to remind students of the elemental composition of plants. Like all living things, plants are made from three main elements: carbon, oxygen, and hydrogen. In corn, these three comprise 94.5% of dry mass (Latshaw & Miller, 1924). In humans, they make up 94% of total mass (Emsley, 1998). Carbon enters the biosphere almost exclusively during photosynthesis, when gaseous carbon dioxide is combined with water to make carbohydrates. Carbon dioxide, either from the air or dissolved in marine or fresh water, is the source of more than 90% of the material assimilated by producers. Water, too, contributes a significant amount of material (Campbell et al., 1999; Freeman, 2008). Everything else – the nitrogen,[6] potassium, phosphorus, sulfur, calcium, sodium, magnesium, and many other

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[4] Miller and Levine (2006) also reinforce the misconception that metabolized nutrients exit animal bodies as defecated waste. Fecal matter is not metabolic waste. It is more accurate to see feces as material that never really entered an animal's body. The vast majority of the organic material that crosses into the body is consumed in cellular respiration and, thus, is not expelled as feces, but rather, *exhaled* CO_2 (Freeman, 2008).

[5] In addition to food and drink, molecular oxygen is incorporated into the bodies of all aerobes when it is converted to water during oxidative phosphorylation. In humans, about 9% of our water needs are satisfied in this way (Committee on Animal Nutrition, 2003).

[6] Whether to consider nitrogen soil-derived or atmosphere-derived is not a simple question. In marine environments, of course, there is no soil. Instead, certain plankton species perform nitrogen fixation, making the atmosphere the main source of nitrogen for most marine systems. In terrestrial environments, nitrogen also enters the biosphere from the atmosphere. However, it is first reduced by soil microbes. Also, unlike carbon, a significant amount of nitrogen is retained in soil after living things decompose (Postgate, 1998). In truth, both the soil and the atmosphere are important nitrogen reservoirs. Still, most textbooks overlook the direct uptake of nitrogen from the atmosphere. Instead, they almost invariably focus exclusively on soil microbes – a fixation they would do well to get over.

essential soil micronutrients – make up less than 5% of the dry mass of a typical vascular plant (Epstein, 1972; Campbell et al., 1999; Freeman, 2008).

Perhaps the most direct proof of the minor role of soil in plant nutrition is also one of the earliest: Jean Baptiste van Helmont's willow tree experiment. Van Helmont transplanted the shoot of a young willow tree into a large pot of soil. He weighed the willow and the soil separately. After watering the tree and watching it grow for 5 years, he uprooted the tree, shook off the soil, and weighed each again. The tree had gained 164 pounds; the potting soil had lost only 2 ounces (Hershey, 1991). We now know that CO_2 and water were the source of the other 163.9 pounds.

Of course, these mass ratios are not just true for willows. Carbon is the sin qua non for almost all cellular biosynthesis. All this carbon enters the biosphere directly from the atmosphere or from atmospheric CO_2 that has dissolved in water.

Because the truth about plant nutrition is often at odds with students' beliefs, an inquiry-based investigation may be the most persuasive. Peruzzi (2009) presents a method for performing a van Helmont-like experiment with students. Similarly, I have suggested an inquiry-based investigation of photosynthesis and cellular respiration that highlights the importance of carbon dioxide transfers and reveals the minor role of soil in plant nutrition (O'Connell, 2008).

○ Conclusion: An Incognito Truth

Although each of the authors criticized above has misled their readers, each also describes the role of atmospheric gases accurately. It is not that *some* experts believe that the biosphere obtains most of its materials from the atmosphere and others do not. All scientific authorities acknowledge the same simple truth: the air, not the soil, supplies the biosphere with the vast majority of its building material. Likewise, all authorities agree that soil is wonderful and sometimes essential stuff. I do not emphasize the minor material role of soil in the carbon cycle in an attempt to deny the importance of soil. We all owe an enormous debt to Steven Hales, Jean Senebier, Theodore de Saussure, Jean-Baptiste Boussingault, and dozens of other scientists who helped discover the mineral nutrient requirements of plants (Epstein, 1972). Their hard-won knowledge has transformed the world, helping to supply food to over 6 billion people (Matthews, 2007). Cultivating the soil has been, and will surely continue to be, essential to the ecological success of humans for the foreseeable future (Foley, 2009). Nevertheless, just because soil is *really*, *really* important, that does not mean it is all-important. If our planet were to suddenly lose every last crumb of soil, life, in some form, would go on.

But like carbon dioxide itself, this truth is hard to see. To the uneducated it sounds preposterous to suggest that an invisible gas and a tasteless liquid are the principal building blocks of tomatoes, blackberries, lobsters, Moses, Aristotle, you, and me. So in addition to simply avoiding texts that publish misconceptions, teachers should present evidence for, and guide investigation of, at least one counterintuitive biogeochemical transfer.

Of course, before teachers can do this, they have to be aware of the misconceptions in the first place. Given the influence of both culture and experience in supporting the Aristotelian view, it is understandable that some teachers might be unaware of these misconceptions. But in fact, these misconceptions seem to be pervasive—even among experts. On its Web site, the publisher of *Living in the Environment* boasts that, since 1975, Tyler Miller's textbooks have been the "most widely used environmental science textbooks in the United States and throughout the world." They have been used by "almost 3 million students and have been translated into eight languages." In addition, Miller's textbook is the required text for three of the four AP Environmental Science syllabi presented as exemplary (see http://apcentral.collegeboard.com/apc/public/courses/syllabi/index.html). The fact that a text with such canonical reach has gone uncorrected for decades is a reminder of the powerful influence of folk beliefs and misconceptions.

If we fail to address such misconceptions in our courses, we risk graduating students who are ill-equipped to understand plant nutrition, climate change, and other fundamentals. Alternatively, if we succeed, our students may realize that scientific knowledge can transform the way they see the world.

A course in biology should make students aware that the muscles propelling them down the soccer field, the hair standing on the backs of their necks, and the very brains they use to understand the world are all built almost entirely from a rare atmospheric gas. Because most students do not experience their muscles, hair, or brains in this way, teachers have a grand opportunity to inspire awed wonder. Richard Dawkins has described such wonder as "one of the highest experiences of which the human psyche is capable. It is a deep aesthetic passion to rank with the finest that music and poetry can deliver" (Dawkins, 2000). It is my hope that correcting misconceptions about biogeochemical cycles will help students experience this wonder.

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DAN O'CONNELL is a biology teacher at St. Andrew's School of Delaware, 350 Noxontown Road, Middletown, DE 19709; e-mail: doconnell@standrews-de.org.