BIOLOGY TODAY

Looking Beneath the Surface for Sustainability

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Since I'm not an ecologist, I can hardly tout myself as an expert on sustainability. However, I did want to contribute an appropriate essay for this issue. An article with the less-than-exciting title "Nitrous Oxide in Flux" (Billings, 2008) gave me an idea for an approach. It reports on a study of how, under simulated drought conditions, forest soils sequester more of the greenhouse gas nitrous oxide (N_2O) than previously thought. Since the mid-18th century, atmospheric levels of this gas have risen 18% due in part to increased use of fossil fuel, crops that capture atmospheric nitrogen, and use of fertilizers. With all these human-driven inputs, anything that reduces the amount of N_2O in the atmosphere would seem to be a plus as far as sustainability is concerned. This of course begs the question of what sustainability means, an issue too large and complex for someone like me to tackle. I'll just write from the viewpoint that it would be wonderful to stop further deterioration of the environment, but at the very least we must slow it down.

The N_2O article interested me for a number of reasons. First, it obviously relates to sustainability. In addition, I always like to be surprised, and in this case, the researchers, too, were surprised by how persistent this N_2O sink was under experimentally managed dry conditions thought to mimic those expected in European forests in the face of global warming. Deep within the soil, N_2O levels are much higher than at the surface. During drought, soil N_2O concentrations near the surface decreased to levels lower than those in the atmosphere, leading to the diffusion of the gas from the atmosphere into the soil. This occurred throughout the forest's growing season, but ended when watering was resumed. This is just one small piece of the puzzle of what will happen with continued global warming, but it suggests that a lot more has to be learned about the soil's role.

Appreciating the Soil

Still another reason for my interest in this study is that it focused on the soil, an environmental component of supreme importance that just doesn't get the attention it deserves. Every so often, there will be an article in a science journal on how important the soil is to plant life, to ecological stability, to water quality, but the fact remains that "out of sight, out of mind" still rules our views of this underground terrain. And not only is it rather inaccessible, but it's awfully complicated as well. In some ways I see its public relations problems as similar to those of the liver, an organ that is vital to life and performs a host of essential functions, from controlling nutrient levels in the blood to detoxifying chemicals–*and* it can regenerate itself. But people don't usually think about the liver until it becomes dysfunctional. I contend that this lack of appreciation is due to the fact that the liver is too versatile. It can be considered as part of the digestive system, the circulatory system, and the immune system, and since we tend to look at the body in terms of systems, we fail to appreciate how multitalented the liver is.

The same seems to be true of the soil. Because it's composed of ground rock, sand, silt, and clay, geologists study it. Microbiologists are interested in all the bacteria and protista it harbors. Botanists see the soil as an anchor for root systems and the place where plant material gets recycled, while mycologists explore the soil because it's home to so many fungi. Just as the liver belongs to no one system, the soil belongs to no one science and is often treated as a minor area in each. But put all these facets together, and suddenly the soil becomes much more significant, particularly today when we are trying to make sense of what humans are doing to the Earth.

An interesting way to approach the soil's many aspects is to look at what Susan Brantley (2008) calls "soil time," the time frames involved in studying different soil components. She notes that the soil is the uppermost layer of the regolith, the loose rock material that covers the Earth's surface. Geologists see the regolith as being in equilibrium with the soil when the rate at which rock fragments are added from deeper geological layers are balanced by the rate at which erosion wears away the regolith's upper layers. As an example, Brantley describes an undisturbed ridgetop in a Puerto Rican rainforest and calculates that the 0.6 meter upper layer of soil would renew itself over a period of 60,000 years. However, other geological changes, like volcanic and tectonic activities, are often described over time frames of hundreds of millions of years to hundreds of years. If attention moves from minerals and rock formations to soil organic matter, then the time frame changes radically and residence times of 100 to 1,000 years come into play, though some of the material may turnover in one to ten years. Ecologists studying ecosystem changes may be looking at periods of tens to hundreds of years, though fires and pest infestations can involve much shorter fluctuations. If water is the focus of interest, residence times in the soil can vary from years to minutes.

Brantley's point in going into this "soil time" review is to argue that while scientists in one particular field tend to deal with one segment of soil time, the environmental issues that soil scientists now have to tackle must entail a broader view: "Learning how soils will change in the future will require observations and models that cross time scales" (p. 1454). She takes as an example the effects of fertilizer use on phosphorus balance in soils. The transport of dissolved phosphorus from land to oceans has doubled, and not only does this have short-term effects but can lead to imbalances in the regeneration of regolith on a time scale of 1,000 to 10,000 years.

Life in the Soil

I will admit that as a biologist, I tend to focus on much shorter time scales, those on the order of organisms' life cycles–and there is definitely a lot of life in the soil. As Amber Dance (2008) very enthusiastically points out: "More creatures live in soil than any other environment on Earth" (p. 724). She then goes on to survey some of these organisms and investigates why it's so difficult to figure out just how many different kinds there are. Once again, the inaccessibility of the soil causes a problem. Just how do you find these guys? Some are more apparent than others. Plants tend to stick up above the surface which makes them easy to see, earthworms are frequently washed out during a rainstorm, and moles sometimes venture from their burrows. A little digging will reveal many more organisms. I am fond of citing entomologist Frank Lutz's (1941) report that when he dug up his suburban New Jersey backyard, a 50 by 100 ft. plot, he found over 1,400 insect species. Dance's numbers are even more staggering. She cites one estimate that there are anywhere from 10,000 to 50,000 microbial species in a gram, yes just a gram, of soil. James Nardi (2007), in his wonderful book on the soil, has a pyramidal diagram showing the number of individuals from vertebrates to bacteria in one square meter of soil. He notes that: "If the dimensions of each layer in the pyramid were drawn proportionally to the number of creatures that they represent, then the layer for bacteria and actinomycetes would be 100 times the volume of the mite layer; and the mite layer, in turn, would be 100,000 times the volume of the vertebrate layer" (p. 27).

This reminds me of still another of my favorite citations, Edward O. Wilson's (1984) statement: "Think of scooping up a handful of soil and leaf litter and spreading it out on a white ground cloth, in the manner of a field biologist, for close examination. This unprepossessing lump contains more order and richness of structure, and particularity of history, than the entire surfaces of all the other (lifeless) planets. It is a miniature wilderness that can take almost forever to explore" (pp. 13-14). This is an important point. Investigating just the microbial wealth is a staggering job, especially because it's still difficult to even define what a microbial species is. Invertebrates are also masters of diversity. One researcher took soil cores from two sites in Alaska, one in the tundra and one in the taiga forest. Though the sites were only a couple of hundred miles apart, they shared only 18 invertebrate taxa out of an estimated 1,300.

There's even great diversity when soil samples are taken just a meter from each other; they can vary a great deal because of differences in moisture or plant cover or nutrient availability. The soil under a decaying plant or animal is very different from that without such enrichment. If you like a complex mystery, it seems that the best place to look is under your feet. As Dance notes: "Even a small clump of soil has a gradient of oxygen from its edges to the center, and each oxygen concentration may make the perfect habitat for different kinds of creatures" (p. 724). It's exciting to think about this, another example of the complexity of life. Of course, it can also lead to discouragement. How can we ever figure out what sustainability means, let alone how to achieve it, if every clump of soil is a intricate world in itself–and I haven't even gotten to the fungi.

Fungi

John Whitfield (2007) cites estimates that a gram of soil can contain 100 meters of mycorrhizal filaments, mycorrhizae being the fungi which grow in or on the roots of approximately 80% of land plants. These fungi are important to the health and growth of plants since they provide extra surface area on the roots allowing greater absorption of water and nutrients, plus protecting against soil pathogens. While the fungi provide a service to plants, they also derive benefit from plants in the form of energy-rich carbon compounds. With so many organisms in the soil, there's great competition for resources, and these fungi may also be involved in a form of nutrient redistribution that is just beginning to be explored in depth. Researchers find that not only do fungi serve as conduits for nutrients to plants, they can also serve as conduits between plants. Carbon compounds taken up by fungi may, in turn, move on to other plants, more parasitical ones that may have forsaken photosynthesis entirely.

Such complex interactions are questioned by some mycologists, but others cite recent evidence for what Whitfield calls a "wood-wide web" (I couldn't resist mentioning that). For example, the serrated wintergreen, *Orthilia secunda*, is a small plant found in the deep shade of northern forests in both Europe and North America. Obviously, it doesn't get much light, but that may not be a big problem for this little plant which apparently has another source of energy besides photosynthesis. Studies indicate that it gets half the carbohydrates it needs from mycorrhizal fungi, which, in turn, are getting them from the roots of trees that overshadow *Orthilia*. This is a beautiful example of symbiosis, but an example that was difficult to discover and measure since it is literally hidden from view. Those who are skeptical of the fungal role here think, instead, that carbohydrates move directly from one plant to another–this is still another question about the soil that requires further research. The very fact that a gram of soil can contain a 100 meters of mycorrhizal filaments suggests that untangling what goes on there won't be easy.

Global Warming

Figuring out what soil is and does is difficult enough, but add to this the fact that it is always changing, especially in the face of global warming, and this makes things even more complicated, as the soil N_2O example I opened with suggests. One area with particularly difficult issues is the Arctic where permafrost has been changing in several different ways as a result of climate change. The most obvious result is melting, which in many areas has undermined buildings and roads. On a long-term basis, however, changes in the thawed soil itself may have more profound consequences. Freezing has preserved leaves, roots, and other organic debris which in temperate zones are decomposed by soil microorganisms. When the permafrost melts, this organic material begins to decay and adds a great deal of carbon to the atmosphere, what Gabrielle Walker (2007) describes as the "great putrefaction."

Not surprisingly, how fast thawing will occur is a matter of debate. One climate model predicts that 90% of northern permafrost will disappear by 2100; even conservative estimates run to a 60% loss. However, these models don't take into account negative feedbacks that seem to be coming into play. Warmer temperatures have resulted in thicker layers of moss growth on the surface of Arctic tundra, providing insulation that can slow melting beneath; areas with the thickest moss cover have the thinnest melting layers below. On the other hand, warming has brought more sunny days which moss don't tolerate well, so if this trend continues, moss growth may slow. Also, as the permafrost melts, water trickles down and freezes, forming a dense layer of ice that also insulates the permafrost. None of these processes prevent melting, but they do seem to put the brakes on it.

As if that weren't complicated enough, there are a number of other processes going on–and changing with changing climate. Warming means more plant growth during Arctic summers, especially because thawing and decomposition pump more nutrients into the soil. In some areas, this means that there's more carbon taken up than released–at least during the warmer months. Thawing also means the soil is wetter, so plants that can tolerate wet roots, like sedges, are becoming more common. In addition, water seals the underlying soil from the air so decomposition occurs without oxygen; this slows down the process and thus lessens carbon release. But that isn't all good news. (What is on the global warming front?) Because of the lack of oxygen, the carbon is liberated in the form of methane rather than carbon dioxide, and the former is a much more potent greenhouse gas.

This complexity can frustrate not only the modelers, but biology teachers as well. It would be nice to be able to present neat, clean cause-and-effect stories to students, but the Arctic tundra obviously isn't the place to look for them. Perhaps we shouldn't even try. Maybe it's a good thing to let students know just how difficult the business of climatic prediction is so they understand why the predictions of global change that they read in the paper or on the Web keep changing. I've dwelt on the tundra example because it's so complicated, so little studied until recently, and so foreign to me. I've never been to the Arctic, and probably should worry more about what is going on much closer to home. But the tundra is a fascinating ecosystem–apparently so stable, yet so fragile, so massive, yet so different from one area to the next. Sometimes I think it's good to move outside of ourselves and our environs. We can look at the tundra more as an ecosystem and less as a political unit than we do with local areas. Yes, we will eventually have to come back home to our own problems, but perhaps "traveling," at least mentally, may give us a new perspective on our own difficulties.

The Land

To return to our country and its soil, there have obviously been issues of soil erosion here for a very long time. This is a huge concern, and I don't have either the space here, or the expertise, to go into it. Years ago, I can remember reading Louis Bromfield (1945, 1948) books on alternative farming methods given away by the local library. He was writing in the mid-century, and more recently Wendell Berry (1981) has also written of ways to farm and preserve the soil at the same time. Both have been seen by many as unrealistic, though views are changing, yet again. Michael Pollan (2006) and Barbara Kingsolver (2007) describe alternatives to factory farms and how these could reduce our use of fossil fuels considerably while improving soil and supplying us with fresher, healthier food. Just as Bromfield did years ago, Pollan and Kingsolver, along with Al Gore and so many others, are getting to at least thinking about the land and how we use it.

Soil loss can be slowed by "no-till" farming, that is, planting seeds in unplowed land. However, this doesn't work well for annual crops like wheat since they don't get their roots deep enough in a single growing season. Jerry Glover, who does research at the Land Institute in Salina, Kansas, is attempting to genetically engineer a perennial form of wheat in a rather novel approach to sustainability (Marris, 2008). Perennial wheat, with deeper roots, would not only make no-till wheat farming more feasible, but in addition would reduce the need for fertilizer. Deeper roots also slow erosion. This all sounds great, but as generations of botanists have learned, plants don't always do what you want them to, even when you manipulate their genes. This is a great example to use with students. Present all the arguments for perennial wheat, and next inform them that at the moment it is little more than a dream crop. Then ask them what makes a perennial different from an annual and see what they come up with.

Corn is another crop on which we are very dependent and on which a great deal of research is done, including how to sustain crop yields despite global warming and the drying conditions which may come with it. Considering crop growth involves thinking about the soil and about the roots that call it home. This can mean going into fields and studying soil in all its complexity, and it can also mean studying roots in test tubes. Plant geneticists are, paradoxically, growing maize seedlings hydroponically to look at how plants deal with drought (Pennisi, 2008). They are investigating gene expression in different parts of the maize root and in different varieties. They've found that different genes are activated along the length of the roots, and some corn varieties are better able to deal with drought than others. Even two strains that can both withstand dryness do it by activating different genes. So here again biologists are faced with a host of complex issues even when they are growing plants in the simplest and most controlled environments.

Having several plant genomes already sequenced, and several more soon to come, should help research on what is going on beneath the soil surface (Whitham et al., 2008). Researchers are now looking to how genomics can spur research on natural communities and ecosystems, as plant genetics is linked to information on fungal, insect, and other genomes. This is truly systems biology writ large. Sequencing the ectomycorrhizal fungus, *Laccaria bicolor*, provided particularly rich results because it can be grown in culture and can associate with tree roots under laboratory conditions (Cullen, 2008). But its genome suggests that more interesting results may come from field studies. While the *L. bicolor* genome has less genes for cellulose degradation enzymes than might be expected from such a fungus, it has more enzymes to break down insect, bacterial, and other organic materials, indicating that it's probably more involved in the degradation of microorganisms and animals than of plants. As with almost every other genome sequenced so far, this one holds surprises, a sure sign that our ignorance of how the living world works has hardly been touched.

I have rarely written a column where questions and ignorance seem to play such a large part. This can be discouraging, as can the whole issue of environmental deterioration and the quest for sustainability. However, I'd like to end with a couple of hopeful signs–good news and results that seem to be pointing in positive directions. One place to begin is in the Amazon region where so much environmental chaos has been caused by deforestation. One such endeavor–to create *Eucalyptus* forests to produce paper pulp–was begun in the 1960s and ended in failure by the late 1970s (Stokstad, 2008). Now those cleared lands have in many cases regrown, and biologists are studying what kinds of secondary forests arose. The swaths of land involved are so large that edge effects are minimized, giving better results than on smaller experimental plots studied in the past. The findings, not surprisingly, are mixed. There are a lot of species missing in the secondary forests: At least 60% of the birds are gone as are many tree species. Bats and fruit flies tended to do better. For some groups, such as mammal and scavenger flies, there wasn't much difference in species number, but many of the primary forest species disappeared. For example, fruit-eating monkeys were replaced by more ungulate browsers. What is hopeful is that secondary growth helped to maintain diversity in adjacent primary growth forests, and overall diversity in the disturbed land was enhanced if the land wasn't completely cleared, with large trees left intact.

Finally, biofuels are the buzz right now in discussions of sustainability, though there is much argument over how feasible they are and which plants should be grown. The glamour has gone out of corn as a biofuel, and perennials like grasses are now seen as more desirable (Brainard, 2007). Waste biomass is another possible source of energy that could be converted into hydrogen fuel and char (Day & Hawkins, 2007). The latter doesn't sound very exciting, but there's research showing that it can be a valuable soil additive since some of the most productive agricultural soils do contain elemental carbon. So through this whole maze of questions and problems, I've managed to land back in a soil that might be sustainable. ●

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